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DEPARTMENT OF THE INTERIOR
FRANKLIN K. LANE, SECRETARY
BUREAU OF MINES
VAN. H. MANNING, DIRECTOR

METHODS FOR INCREASING THE RECOVERY FROM OIL SANDS

BY

J. O. LEWIS

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METHODS FOR INCREASING THE RECOVERY FROM OIL SANDS.

By J. O. Lewis.

INTRODUCTION.

In its efforts to reduce waste, and increase efficiency in oil production, the Bureau of Mines is investigating methods of increasing the recovery from the underground sources of supply, which are the foundation of the petroleum industry and the many allied industries wholly or partly dependent on it. In the face of a demand that is increasing faster than the production and that, in the consensus of opinions of well-informed authorities, is soon likely to outstrip the productive capacity, it is well to consider whether it is not possible to extract more oil from the known sources of supply. It is universally acknowledged that by the usual production methods much oil is left underground, the general opinion being that at least 50 per cent of the oil in a field remains unrecovered when the field is abandoned as exhausted. From the writer's own investigations he believes the average recovery is even less, and if any considerable portion of this oil being left underground could be made available it would have a tremendously favorable influence on the petroleum industry and all the industries dependent on it.

In this publication are considered the principles involved in increasing recovery and methods of extracting more oil from the oil-bearing formations than by the usual ways of producing. These methods are: The use of gas or vacuum pumps, forcing compressed air or gas through the oil-bearing formations, displacing the oil by water, and better utilization of the natural pressures in the oil-bearing formations. Especial attention is being given to a process—commonly known as the Smith-Dunn—for forcing compressed air through oil-bearing formations because it is believed to hold most promise for the future.

ACKNOWLEDGMENTS.

The author desires to give particular credit to Messrs. I. L. Dunn, Orton C. Dunn, and Harvey E. Smith, of Marietta, Ohio, from whom most of the information on the above-mentioned process was ob-

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GENERAL STATEMENT.

That much of the oil in a field is never recovered is well known, but how large a proportion is left underground and the possibility of increasing the recovery can not be fully realized until one clearly understands that the exhaustion of an oil well is due more to the exhaustion of the natural gas, which is the principal agent in driving the oil into the well, than to the exhaustion of the oil itself.

Facts presented in this bulletin go to show that the capacities of the oil sands in the various fields of the United States are five to ten times greater than the quantities of oil commonly extracted from them. If it could be fully established, as seems most probable, that the pores of the oil-bearing sands were completely filled with oil at the time the fields were first developed, then 80 to 90 per cent of the oil is left underground when the wells are abandoned. Although the evidence at hand does not permit positive statements that this proportion is being left underground, there is abundant evidence that much oil capable of being recovered remains in the sands. Complete extraction is not to be hoped for, yet there is no reason to conclude that the maximum possible recovery has been reached when the natural forces have been exhausted, and, furthermore, it has been demonstrated that it is practicable to get more oil from the sands by the processes described in this report.

It is too soon to know just how much to expect from these methods of increasing recovery, but the results have been so encouraging that they give possibilities of new values to the properties of every producer and to the country as a whole as a new source of supply to ward off the threatened shortage. It would thus seem the part of wisdom for the individual producer and for the general public to see that the oil fields are left in condition to use these or any new or improved processes that may be discovered in the future. It should be insisted, as far as practicable, that oil wells not now profitable be abandoned in such manner that they may be reclaimed at some later date, when, as seems probable, new discoveries and improved economic conditions will make their operation profitable once more.

The problem of increasing recovery divides itself naturally into two phases—a better utilization of the natural forces in the oil-bearing formations and the employment of artificial pressures. Under present conditions probably the only generally feasible methods for recovering more oil from the formations after the natural forces have been exhausted involve the forcing of gases or liquids through the oil-bearing formation. Of the gases that might be used, only air and natural gas are practically available, and of the liquids only water.

The oldest and most extensively used of the methods previously mentioned is gas or vacuum pumping. By this method the pressures at the wells are reduced, permitting further expansion of the gas and the expulsion of more oil from the oil-bearing formations, but experience has shown that it is not adapted to all localities, and where used has only slightly increased the total recoveries from the fields. Productions of wells may be increased several times, but the benefits are temporary and the additional expenses of operation usually consume the additional gross value of the production. Were it not for the gasoline extracted from the increased volume and enriched gas, gas pumping would seldom be profitable.

Displacing the oil from the pores of the oil-bearing formations by water, commonly known as flooding, has seldom been successful, the conspicuous exception being in the Bradford field, Pennsylvania, where letting fresh water into the oil sand undoubtedly has resulted in increased recovery. As flooding practically ends all further possibilities of increasing recovery by other methods, its employment until other methods have been tried seems a shortsighted policy, even where positive results have been obtained and conditions are believed to be exceptionally favorable, as at Bradford. Elsewhere flooding has ordinarily done more harm than good, and in the occasional instances where a property has been benefited it is usually at the expense of other properties near by. Flooding has been held in general disfavor, though a few advocates have claimed that the faults lie mostly in the ways in which it is applied. In the writer's opinion natural conditions preclude its extensive success, and it is doubtful whether as much oil is being obtained, even under the exceptionally favorable conditions at Bradford, as would be possible by other means. Certainly its use in untried fields is hazardous.

In the Smith-Dunn process, also known as the Marietta process, through its first extensive use at Marietta, Ohio, compressed air is forced into the oil-bearing formation through a few of the wells on a property, thus forcing the oil underground toward the other wells, from which it is pumped in the usual way. The process has been successfully used for nearly six years and has been applied to about 100 properties, including about 4,000 wells mostly located in the Appalachian fields. It has been successful in at least 80 per cent of the cases where used, and the records of 32 properties show an average increase of three and one-half times the production at the time the process was started. The process offers such possibilities of extended application and of further improvements that it is thought to be the most promising of the methods so far advanced for increasing recovery. Natural gas can be used similarly, but because of the scarcity and value of natural gas where such methods will be resorted to, its use will less often be practical.

As the exhaustion of a well depends principally upon the exhaustion of the gas associated with the oil, more efficient utilization of the gas in forcing the oil from the productive formation would result in increased extraction. Only limited efforts have been made to apply this principle practically, but it deserves extended investigation. The employment of the Marietta process, wherein the movements of the oil and air can be traced, has disclosed much information capable of being applied profitably to the production of oil by natural forces.

In this bulletin the writer has discussed the theoretical and the experimental data in some detail. Possibly the bulletin could have been made more useful to the industry as a whole by confining it more closely to the practical aspects of the subject. However, the author thinks that as the report is to be put before the industry when entering an entirely new phase, that of increasing the extraction of oil from old fields instead of exploiting new fields, the publication of the principles involved and the presenting of most of the information at hand were desirable. The writer realizes that the majority of practical men will not choose to go into the subject deeply, but will prefer to learn from others who have used the process; but for the ninety and nine who always follow there is the one who leads, and it is hoped that the benefits that he may derive from treating this subject fully, and the others indirectly through him, will justify the manner of treatment. It has been the endeavor to present the practical information in such a way that a reader once familiar with the report can readily find what is desired and avoid the rest.

SOME PHYSICAL PROPERTIES OF PETROLEUM AND GASES.

In the following brief discussion of certain physical properties of petroleum and gases only the factors of relatively greater importance to the recovery of oil are considered.

CHARACTER OF CRUDE OILS.

Crude oils or petroleums are mixtures of bituminous hydrocarbons, some of which are solids, some are liquids, and some are gases, the solids and gases being soluble in the liquids. A crude oil may consist of these various hydrocarbons mixed in almost any proportions, its physical properties varying accordingly. An oil may contain a quantity of the solid hydrocarbons like asphalt or paraffin and be heavy and viscous, whereas another oil may consist largely of the lighter fractions such as kerosene and gasoline and be correspondingly light and fluid.

THE SOLUBILITY OF GASES IN PETROLEUM.

The gas held in solution by the oil is an especially important factor in the recovery of oil from the formations in which it is found. Under the same conditions of temperature and pressure a particular oil will absorb a fixed proportion of a particular gas, but this proportion or coefficient of absorption, as it is called, varies with each oil and each gas. The gas is held absorbed in the oil in the same way that soda water is charged with carbon dioxide. The proportion of gas absorbed is lessened under high temperatures, but is greatly increased under high pressures, in accordance with Henry's law of gases. Enormous quantities of gas are held in solution under the high initial pressure found in some oil wells. Some of the constituent gases are condensed at these high pressures just as in a compressor plant, and as long as high enough pressure is maintained exist as liquids dissolved in the oil. Under such conditions the gas is not absorbed as a gas but as one liquid dissolved in another, and a much greater proportion of gas can be held in solution when in liquified form than when uncondensed. Other gases (methane, ethane, and propane) are never liquified at the pressures and temperatures in oil sands penetrated by wells, but are always found as gases dissolved or absorbed in the oil.[a] They constitute the so-called dry gases.

There is little available information on the solubility of natural gases in crude oils. Burrell[b] has stated that actual tests showed certain California oils absorbed about 15 per cent of their volumes of the natural gas used in Pittsburgh, Pa. The solubility of certain gases in Russian petroleum is shown by Gnieswosz and Wolfies[a] to be as follows:

---

[a] Burrell, G. A., Seibert, F. M., Oberfell, G. G., The condensation of gasoline from natural gas: Bull. 88, Bureau of Mines, 1915, p. 29.

[b] Letter to author.

Absorption coefficients for petroleum.

Gas.	Absorption in petroleum.		Absorption in water at 20° C. (68° F.).
	At 20° C. (68° F.).	At 10° C. (50° F.).	
Nitrogen .... per cent..	11.7	13.5	1.40
Oxygen .... do....	20.2	27.9	2.84
Methane (marsh gas) .... do....	13.1	14.4	....

These figures are especially interesting as showing the relative solubilities of the two chief constituent gases of air (which contains, approximately, 80 per cent nitrogen, 20 per cent oxygen) and methane, which is the principal constituent of most petroleum gases, especially during the early lives of the wells. They also show that probably the solubility of air is not much less than that of natural gas high in methane. The solubilities of the other petroleum gases, ethane, propane, and butane, are much greater, as is shown in Bulletin 42,[b] Bulletin 88,[c] and Technical Paper 45,[d] so that the gases released at low pressures as in vacuum pumping, have far greater solubilities than methane and air.

When the pressures are not too high, considerable quantities of vapors from the lighter constituents in the oil are carried by the gases, just as water vapor is carried in the atmosphere. The carrying power of all gases is the same, provided no chemical reactions take place, and air can carry just as much gasoline vapor as can natural gas. The vapor-carrying power is decreased by high pressures, and increased by high temperatures. Under a given temperature and pressure the proportion of vapor a gas can carry will vary according to the nature of the liquid from which the vapor is derived. Burrell gives the following figures on the maximum carrying power of air for vapors of light petroleum distillates at atmospheric pressure.[e]

---

[a] Gnieswosz, S., and Wolfies, A., Absorption of gases by petroleum: Ztschr. Phys. Chem., Bd. 1, 1887, p. 70.

[b] Burrell, G. A., and Seibert, F. M., The sampling and examination of mine gases and natural gas: Bull. 42, Bureau of Mines, 1913, pp. 97–98.

[c] Burrell, G. A., Seibert, F. M., and Oberfell, G. G., The condensation of gasoline from natural gas: Bull. 88, Bureau of Mines, 1915, pp. 47–48, 69.

[d] Blatchley, R. S., Waste of oil and gas in the Mid-Continent fields: Tech. Paper 45, Bureau of Mines, 1914, p. 44.

[e] Burrell, G. A., Hazards in handling gasoline: Tech. Paper 127, Bureau of Mines, 1915, p. 9.

Proportions of different grades of gasoline vapor that air will carry at a temperature of 17.5° C. (63.5° F.).

Grade of gasoline.	Proportion of gasoline vapor (per cent).
Cleaner's naphtha	5.0
64° B. gasoline	11.0
69° B. gasoline	15.0
73° B. gasoline	28.0

It will be noted that the lighter the gasoline the greater the quantity of its vapor which a gas can carry.

As the pressure is reduced in a producing oil sand the absorbed gases are released from solution and the liquefied gases expand and become true gases while quantities of gasoline vapor are carried in the gases. At every reduction of pressure there is a corresponding liberation of gas and an increase in the quantity of gasoline vapors, so that the gas becomes richer and richer as the pressure is reduced, and is more desirable for the making of gasoline. In the expansion of the gases, as the pressure is reduced, an enormous amount of energy is released which is the principal force in driving the oil from the sand into the wells.

The relative proportion of oil and gas in the oil sand varies in the different fields. Often there is more gas than can be held in solution under the pressures in the oil sand, and under such circumstances the excess gas is found in separate bodies, either in a higher part of the same oil sand or in other sands overlying the oil. As the pressures generally increase with depth, usually more gas is found absorbed in the oil in the deep sands at the higher pressures, and consequently the oil contains more potential energy.

VISCOSITY, CAPILLARITY, AND ADHESION.

The physical properties of viscosity, capillarity, and adhesion of an oil have an important effect on its extraction from the oil sand, as they tend to oppose the expulsion of the oil from the sand, and must be overcome in processes for increasing the recovery of oil.

VISCOSITY.

Viscosity is defined as the internal friction of a fluid. Oils of low viscosity, like the light oils of the eastern fields, flow rapidly, whereas the thick heavy oils of California, with high viscosities, flow slowly. The viscosity of an oil is greatly decreased by heat and increased by cold. Viscosity retards the movement of the oil, but given sufficient time its effect will be overcome even by relatively low pressures.

CAPILLARITY.

Capillarity is the property that causes a liquid to be drawn into small narrow spaces even against the force of gravity. Oil rising into a lamp wick, or ink soaking into a blotter, are familiar examples. A piece of dry sandstone, or a tube full of dry sand, will draw oil up into it in the same manner, and this oil will not drain out naturally. The oil will rise rapidly at first and then slower and slower, but given sufficient time oil will rise into sand or sandstone for some distance, which, however, will seldom be more than 18 inches above the level of the fluid. Near the fluid level, the sand or sandstone will be found to be almost completely saturated, but at the top of the capillary rise the pore spaces will be only partly filled with oil. The rise of the oil in the sandstone will depend upon the character of the oil (its surface tension and specific gravity), the temperature, and the fineness of the sand. The principal factor is the fineness of the pores in the sand, the oil rising much higher the finer the pore spaces are. If oil is poured through sand it will be found that some of the oil will be retained in the finer pore spaces or at the point of contact of the sand grains even though it is above the limit of capillary rise. Figure 1 illustrates this condition.

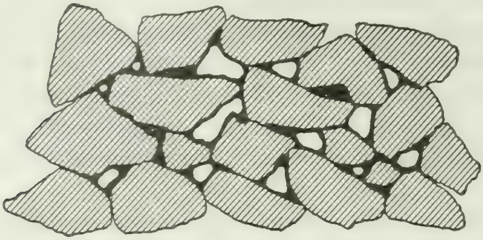

FIGURE 1.—A pile of sand grains, showing how oil is retained by capillarity and adhesion.

ADHESION.

The term adhesion is herein used to designate the adhering of a film of liquid to the surface of a solid such as a grain of sand. If a sheet of glass is dipped into oil, part of the oil will not drain off, but remains wetting the surface of the glass. In the same way a sand from which oil has been drained will have the surface of each grain wet with oil as well as having oil held in the finest pore spaces and in the angles of contact of the grains. The film of oil on each sand grain is very thin, but on account of the enormous aggregate surface area of all the grains in a fine-grained sand or sandstone, a considerable quantity of oil may be retained in this way. In fine uncemented sand there may be an aggregate surface of several hundred square feet in a cubic foot of packed sand.

CHARACTER OF OIL SANDS.

Sands and sandstones are by far the most important oil-producing formations. Next in importance is porous limestone, and occasionally oil is produced commercially from other porous formations such as fractured shales, or vesicular lavas.

VARIATIONS IN CHARACTER OF OIL SANDS.

An oil sand may be loose and hardly more consolidated than a beach sand, like some of those found in California and Texas, or it may be as hard and compact as building stone, such as those found in the Appalachian fields. The sand grains may be almost microscopic in size, or as large as pebbles, and they may be angular or well-rounded, of uniform size or variegated. The sand may be clean and free of silty material, mica, or natural cement, or the interspaces may be almost entirely occupied by such material. The porosity may be over 40 per cent or less than 10 per cent. All these differences influence the yield of oil, the quantity retained after the exhaustion of the gas, and the movements through the sands of water, oil, gas, or air. These variations are the causes of many of the problems to be solved in increasing recovery.

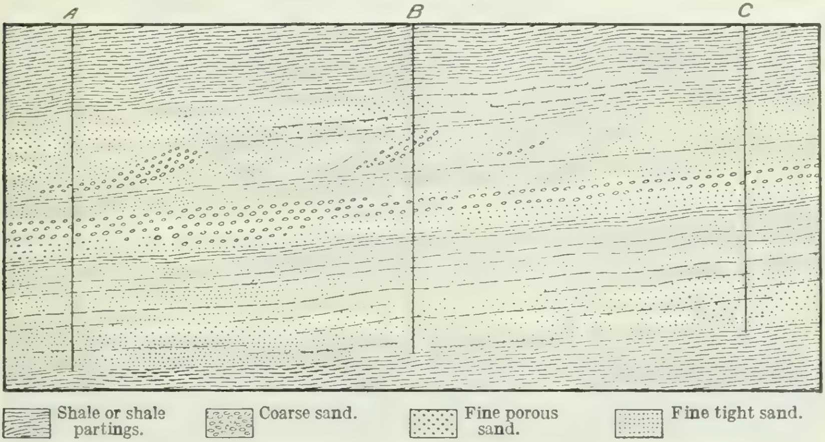

FIGURE 2.—Sketch of an oil sand showing variation in texture and bedding.

The arrangement and shapes of the pores in dolomitic limestones are not the same as in sands and sandstones; consequently they will have different effects upon the retention of oil and the movements of fluids through them. These factors may prove of much practical importance in forcing air through the rock to increase recovery, as has been shown by experience with the Smith-Dunn or Marietta process in wells in the Trenton limestone of Ohio and Indiana. The natures of the pores in sands, sandstones, and dolomitic limestones are shown in figure 1 and Plates I, *A*, and II.

An oil sand consists of many strata of different textures and characters, as shown in figure 2, being in reality a group of sands, frequently separated by more or less impervious layers. These breaks, or shale partings, may be so thin that they are not noticed in drilling, yet they will separate locally one layer from the other as effectively as though they were several feet thick. In all strata it is much more difficult for liquids or gases to move across the bedding from one layer into another than along the bedding. Examinations of the outcrops of sandstones disclose these facts, while in drilling new wells or deepening old wells it is frequently found that a difference of a few inches in depth will make a tremendous difference in the capacity of a well, showing that the drill has passed through a tight part of the sand into an open part.

Similarly an oil sand or one of its layers is never of the same texture throughout the area of the field. A well at one location will find a good production, while at the next location the sand may be so tight that it will yield practically no oil, or the sand may be entirely replaced by shale. In some places the sand layers are evenly stratified; in other places the layers are cross-bedded and irregular in thickness and texture. These variations may occur within short distances and with no regularity, so that porous streaks through the formation will cause liquids or gases to travel between wells in the most erratic ways. Occasionally an oil sand is claimed to be uniform over a whole field. as at Bradford, Pa., but this is only relatively true, as important variations are found there also.

THE POROSITIES OF OIL SANDS.

The porosity or voidage is greater in a clean, even-grained uncemented oil sand regardless of the size of the grains. Where the grains are not of uniform size, the smaller grains may fill the spaces between the larger grains and thus reduce the porosity. Silt and cementing material likewise reduce the porosity.

Porosity is one of the primary factors of productiveness, as it represents the capacity of a sand for storing oil. "Pay streaks" are the most porous or coarsest parts of the oil sand and yield oil most readily, yet it is a mistake to assume that all the oil is derived from one comparatively thin part of the sand body, for productiveness is largely a relative factor and no part of a sand is entirely lacking in porosity.

So little information was available on the porosities of sands actually producing oil that it was necessary to take data published on building stones, water supply, agriculture, and general engineering. These data are believed to represent fairly the capacities of productive sands of corresponding types because there are no general differences between productive and unproductive sands except as to contents, although the latter include some sands that, even if they were oil bearing, probably would be incapable of commercial production because their porosities would be too low or their pores too small.

King shows the average porosity of 135 samples of uncemented sands and soils to be nearly 34 per cent.[a] The generally accepted figure in engineering, water supply, and agricultural publications is

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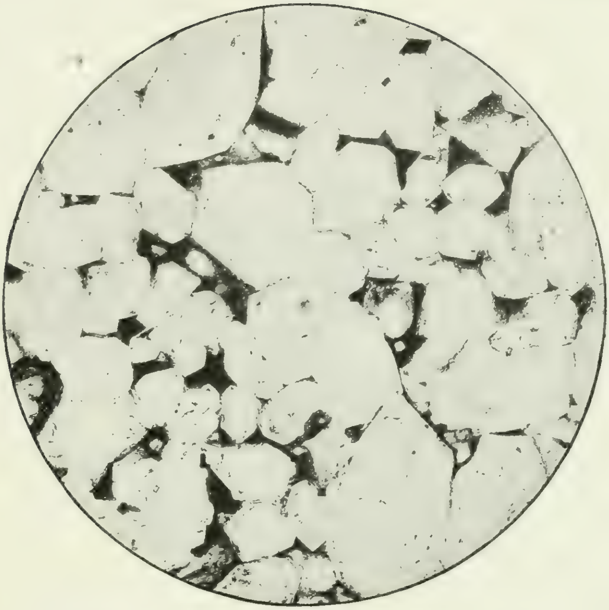
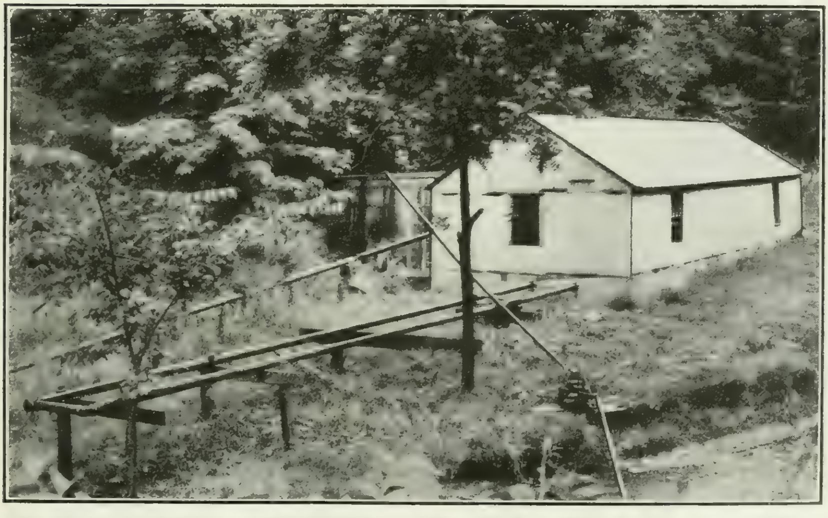
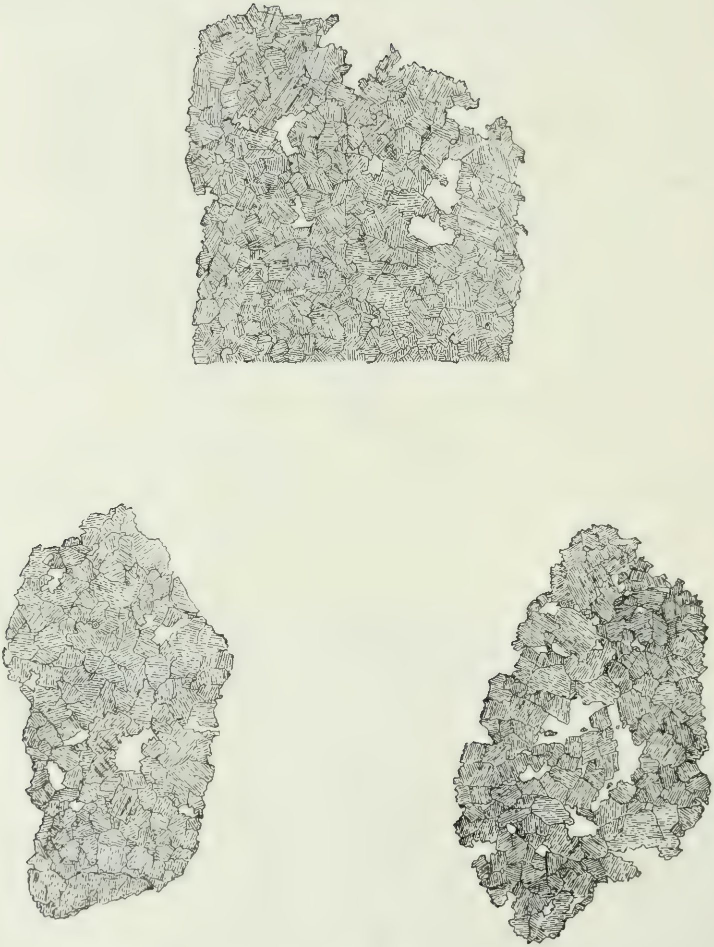
[a] King, F. H., Conditions and movements of underground waters: U. S. Geol. Survey, 19th Annual Rept., pt. 2, 1899, pp. 209–15.



A. ENLARGEMENT OF A WELL-CEMENTED SANDSTONE, SHOWING NATURE OF PORES. AFTER VAN HISE.



B. AIR-COMPRESSOR PLANT NEAR MARIETTA, OHIO, SHOWING PIPING FOR COOLING THE AIR.



ENLARGED SECTION OF TRENTON LIMESTONE, SHOWING NATURE OF PORES. AFTER ORTON.

30 to 35 per cent porosity for clean unconsolidated sands. Porosities of the uncemented oil sands of California range up to 40 per cent, and many individuals report tests showing 30 per cent or more. For California oil sands, an average porosity of 25 per cent is estimated, which is believed to be a conservative figure in view of the evidence.

Table 1 shows the porosities of about 200 sandstones of the building-stone type. Based on these data the porosities of the oil sands of the Appalachian fields are estimated to average 12½ per cent, and for the Mid-Continent fields and Illinois, 17½ per cent. In considering the porosities as given in the table, two facts should be noted. First, the ordinary methods of determining the porosities of sandstones generally lead to low results; and, second, building sandstones are chosen for hardness and low porosity, whereas oil sandstones are of the softest, the least compact, and the most porous varieties in each district. Undoubtedly, the average porosities, especially those computed from "ratios of absorption," are too low, and these figures include many sandstones of the types that are considered to be too tight for production in an oil field.

TABLE 1.—*The porosities of sandstones.*

Locality.	Number of tests.	Porosity.		Character of rock.
		Limits.	Average.	
Mexia, Tex.[a]	....	16.60 to 34.20	25.40	Gas sand.
Petrolia, Tex.[b]	....	18.50 to 27.00	[i] 22.75	Do.
Ohio [c]	6	15.87 to 17.83	16.63	Berea grit (building stone).
Missouri [d]	6	7.01 to 23.77	17.74	Building stone.
Wisconsin [e]	32	4.81 to 28.28	15.89	Do.
Washington [f]	3	10.61 to 18.00	13.17	Do.
Europe [g]	7	6.90 to 25.50	[i] 16.20	Do.

Locality.	Number of tests.	Average ratio of absorption.	Computed porosity.[j]	Character of rock.
Northeastern States [h]	25	2.66	5.98	Building stone
Ohio and Indiana [h]	29	5.22	11.75	Do.
Wisconsin, Minnesota, Iowa, Missouri, Michigan [h]	34	7.93	17.84	Do.
Colorado, Utah [h]	27	9.85	22.20	Do.
Other localities [h]	10	5.89	13.25	Do.
Total or average	134	6.50	14.60	

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[a] Matson, G. C., Gas prospects south and southeast of Dallas, Tex.: Bull. 629, U. S. Geol. Survey, 1916, p. 92.

[b] Shaw, E. W., Gas in the area north and west of Fort Worth, Tex.: Bull. 629, U. S. Geol. Survey, 1916, p. 36.

[c] Bownocker, J. A., Building stones of Ohio: State Geol. Survey Bull. 18, 4th ser., 1915, p. 77.

[d] Buckley, E. R., The quarrying industry of Missouri: Missouri Bureau of Geology and Mines, vol. 2, 2d ser., 1904, p. 317.

[e] Buckley, E. R., Building and ornamental stones of Wisconsin: Wisconsin Geol. and Nat. Hist. Survey Bull. 4, econ. ser. No. 2, 1898, p. 402.

[f] Shedd, S., Building and ornamental stones of Washington: State Geol. Survey Annual Rept., for 1902, vol. 2, 1903, pp. 134–136.

[g] Foester, —, Baumaterialenkunke, vol. 1, p. 13.

[h] Compiled from: Merrill, G. P., Stones for building and decoration, 1891, pp. 504–507; Hopkins, T. C., Carboniferous sandstones of western Indiana: 20th Annual Rept. Dept. Geol. and Nat. Resources of Indiana, 1895, p. 323; Buckley, E. R., Building and ornamental stones of Wisconsin, Bull. 4, econ. ser. No. 2: Wisconsin Geol. and Nat. Hist. Survey, 1898, p. 414; Smock, J. C., Building stone in New York, Bull. New York Museum, vol. 2, No. 10, September, 1890, pp. 195–395. Bain, H. F., Properties and tests of Iowa building stones: Iowa Geol. Survey Annual Rept., 1897, vol. 8, 1898, p. 410.

[i] Mean.

[j] Porosity computed by multiplying the ratio of absorption by a factor of 2¼, which is justified by Buckley, E. R., The quarrying industry of Missouri: Missouri Bureau of Geology and Mines, vol. 2, 2d ser., 1904, p. 303.

White[a] from tests estimated the porosities of West Virginia oil sands to range from 10 to 20 per cent. Carll[b] from tests of Pennsylvania oil sands admittedly made in a crude way estimated the porosity to be from one-fifteenth to one-tenth.

EFFECTS OF TEXTURE AND CONTENTS OF A SAND ON MOVEMENTS OF LIQUIDS OR GASES.

The texture of an oil sand has an important effect on the frictional resistance to the movement of any fluid passing through it. The following table adapted from Slichter[c] illustrates the effect of the relative size of the grains and porosities of sands upon the resistance to the movement of water through it:

TABLE 2.—*Relative velocities of water moving through sands of different porosities and size of grains under the same temperature and pressure.*

Kind of sand.	Diameter of grains, in fraction of an inch.	Relative velocity of water through sand having porosity of—		
		30 per cent.	34 per cent.	38 per cent.
Very fine	1/254	0.003282	0.004960	0.007170
Fine	2/254	.01315	.01983	.02865
Medium	4/254	.05270	.07940	.1145
Coarse	8/254	.2105	.3175	.4585
Fine gravel	50/254	8.220	12.40	17.90

The movements of oil, gas, or air will be affected just as much as that of water by the texture of the sand, a relatively slight difference in texture making a large difference in the resistance. For example, decreasing the porosity of a sand by about one-fifth increases the resistance more than two times, and if the sand grains are decreased to one-half the former size the resistance is increased four times. Between the very fine sand and the fine gravel of the same porosities there is a difference in resistance of 2,500 times. This means that air, gas, oil, or water would advance along a layer of the fine gravel about 2,500 times faster than along a layer of very fine sand.

Besides the texture of the oil sand, the character and distribution of its contents influence the movements of other fluids through it. Water moves through sands more readily than oils, especially the heavy, viscous oils, and air and gas move through far more readily than either. For these reasons a barren or partly drained part of the oil sand will offer less resistance to the movements of air, gas, or water than the other parts, provided this effect is not counteracted by differences in texture.

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[a] White, I. C., Petroleum and natural gas: West Virginia Geol. Survey, vol. 1A, 1904, p. 45.

[b] Carll, J. F., The geology of the oil regions of Warren, Venango, Clarion, and Butler Counties: Second Geol. Survey of Pennsylvania, vol. 3, 1880, p. 251.

[c] Slichter, C. S., Field measurements of the rate of movement of underground waters: Water Supply Paper 140, U. S. Geol. Survey, 1905, p. 12.

Experiments showed how the movements of air or gas are influenced by the contents of a sand. A tube was packed tightly with the fine sand saturated with a California oil of 25° B. used in Table 3. Compressed air from a small laboratory compressor was forced through the tube at the full capacity of the compressor. The results are tabulated below.

Expulsion of oil from a sand by compressed air.

Total time.		Total recovery.	Pressure.
Hrs.	*min.*	*Per cent.*	*Pounds.*
	3	....	125
	5	50	45
	10	55	....
	15	57	....
	45	64	35
1	15	66	....
1	45	67.5	30
3	15	69.5	....
17	15	72	28

The first oil was expelled at 50 pounds pressure. The tube full of sand before being filled with oil showed a resistance of 18 pounds. Similar results were obtained in other experiments, the resistance to the movements of air or gas decreasing greatly with the decrease in saturation of the sand, although the volumes of free air forced through the sand at low pressures were considerably greater than at the higher pressures.

When air, gas, or water is forced into an oil sand it tends to follow the line of least resistance, governed mostly by the texture and the contents of the sand. If a part of the sand is dry, or formerly contained nothing but gas, it will be in the line of least resistance provided the texture is not too tight. If there is no gas sand, the line of least resistance will probably be through the former pay streaks or possibly the water channels. Water tends to follow along the bottom of the sand and down the dip, whereas gas or air tends to flow in the opposite direction, but in the eastern fields especially these tendencies are apt to be modified or overcome by the character and contents of the various layers of sand, which will be relatively more important. Where the top of the sand layers has been partly drained of oil it will afford a channel of less resistance, and likewise where there is less gas pressure will be a line of low resistance. Progressively with the extraction of the oil from the sand, the gas, air, or water tends to follow the parts of the formation where least oil remains.

EXPULSION OF OIL FROM A SAND.

When a well is drilled through the impervious strata capping an oil sand the pressure is released at that point and an avenue of escape for the oil and gas is afforded. The gas absorbed in the oil immediately expands and flows toward the hole, moving oil with it. As there is less frictional resistance to the movement of the gas it moves much faster than the oil, and consequently the gas is exhausted first. While the pressure is high only the dry gases absorbed in the oil are liberated, but as the pressure is reduced by the escape of gas, the wet gases, liquefied and dissolved in the oil, are released and supply energy. The composition of the gas changes as the pressure is reduced, the proportion of ethane and other higher hydrocarbon gases and vapors increasing so that the gas begins to get "wet" and becomes valuable for the extraction of gasoline by compression. There comes a time in the life of the well, provided it is not prematurely cut off, when practically all of the force of the compressed gas absorbed in the oil has been expended and gravitation is the principal remaining force. The movement of the oil then may become so slow that it does not flow into the well rapidly enough to make a profitable production, and the well is abandoned, although only a minor part of the oil may have been removed from the sand. The well is said to be exhausted, yet in reality it is not the oil, but the expulsive forces which have been exhausted.

The gas absorbed under pressure in the oil, or possibly entrapped in the pores of the sand, is the principal source of energy for expelling the oil from the sand. Occasionally the flow of oil is assisted by the pressure of free undissolved gas which may overlie the oil in the same sand body or by the movements of water. Gravitation is comparatively a weak, slow-acting force, especially where the dips of the oil sands are low and where the sand is irregular in texture and bedding, these being the commonest conditions in the oil fields of the United States. The decrease in production follows closely the decline of gas pressure at the well, and when the pressure is practically exhausted the well reaches a very low production, although much oil may remain in the sand. This shows that gravitation alone moves the oil so slowly that it has little practical effect. Experiments indicate the same fact, and there can be no doubt that the predominant expulsive force is the energy stored in the compressed gas absorbed in or associated with the oil. This is also the common opinion of others who have considered the subject for the major part of the oil recovered from a field is produced during the periods when the wells flow or are pumped so "high off bottom" that little or no oil could drain out of the sand against the column of fluid standing in the hole.

HOW OIL IS RETAINED IN THE SAND.

The expulsion of the oil from the sand is retarded and opposed by viscosity, capillarity, adhesion, and frictional resistance in the sand. It has been shown that viscosity is greatest for heavy oils and at low temperatures, and how the other factors are most important in fine sands of low porosity, especially if thinly or irregularly bedded. Frictional resistance is further increased by the sands being clogged by the deposition of waxy materials from oils of paraffin base or by the accumulation of silty materials or "floating sand" in the pores of the sands. A portion of the energy released from the expanding gas is used up in overcoming the resistance from these causes, but in addition much of the energy is wasted, owing to the escape of gas without doing work. There is a marked tendency for the gas to slip by the oil through the larger pores of the sand and through parts of the sand body offering least resistance without expending much energy in actually moving oil, this tendency increasing enormously with the removal of the oil, as shown by the experiment cited previously.

It is likely that in sands where there is the greatest opposition to the expulsion of oil—that is, in fine sands of low porosity and with heavy oils—there will be relatively less waste of energy, for the gas will not be so apt to slip through the sand without moving oil. This probably explains why tight sands and heavy oils usually give wells that maintain their productions very steadily. But the more irregular the texture and the character and proportion of contents of a sand body the greater will be the waste of energy which is essentially like the "by-passing" of air in the Smith-Dunn or Marietta process that has proved to be one of the chief difficulties to overcome in the use of compressed air.

The proportion of oil recovered from an oil sand may be said to represent a balance of the energy originally stored in the oil sand with the waste of energy and the opposition to the expulsion of the oil. This might be termed the "efficiency of expulsion," and will depend not only on the natural conditions but also upon the manner in which the producer operates his wells. While the operator can not control the original conditions of energy and resistance in the sand, he can partly control the efficiency of expulsion. As it is the energy contained in the compressed and absorbed gas rather than the oil that is exhausted, it is but logical to judge the efficiency of a producing method largely by the relative quantities of gas produced with each barrel of oil. If by a change in method the producer lessens the proportion of gas with each barrel of oil, he should increase the total recovery of oil correspondingly, even if the rate of production is temporarily reduced somewhat.

Of the oil retained in the sand after a well has reached economic exhaustion under the customary production methods, part is retained so tightly by capillarity in the finest pores as well as by adhesion to the surfaces of the sand grains (fig. 1) that its removal seems to be possible only by using heat or solution. How much oil may thus be retained is shown by Table 3, although other experiments have disclosed that a somewhat greater proportion, especially of the heavier oils and in the finer sands, may be removed by the continued passage of compressed air or gas through the sand. This quantity retained appears to mark the ultimate limits of recovery of any of the methods discussed in this paper, but between this probably irrecoverable minimum and what ordinarily has been left in the oil sands there is a vast quantity of oil that can be recovered by the agencies discussed. This includes oil that in time would drain out naturally, and oil that is trapped in the sands by water or pocketed in irregularities in the sand body. Some other forces than gravity or the weak gas pressure remaining in the sand are required to expel such oil at a commercial rate.

Probably the bulk of the oil retained in the sand is oil that theoretically can be recovered. How viscosity and frictional resistance retard the movements of the oil has been discussed. After the sand has been partly drained the movement of oil is so retarded from these causes that it becomes exceedingly slow even under the most favorable conditions. Usually the oil sand is split into many layers and lies nearly flat so it readily may be understood how much oil might remain in the sand and yet the well not yield commercial production. A measure of the force of gravitation under these conditions may be gained from considering the results from using vacuum pumps on wells that are nearly exhausted. Reducing the pressure only 10 to 12 pounds will often double or treble the production for the time being.

It has been shown how capillarity holds the oil in the sand, more oil being held at the base and less toward the top. The proportion retained will be largest in the finest grained sands, and the proportion will be greatly increased where the sands are thinly and irregularly bedded. Every impervious or semi-impervious streak of shale or other material, no matter how thin, will act as a base for capillarity, although if the beds dip steeply much of the oil will drain down the slope by gravity. Likewise streaks of coarser or more porous sands will cause the retention of more oil in the finer parts of the sand, as disclosed by the experiment cited in another paragraph. Where the sand is nearly level and is split by many shale partings, or tight or coarser streaks, a large proportion of the oil may be held by capillarity.

The proportion of oil that may be retained in this way is indicated by Table 3, which gives the results of a few laboratory experiments. In these tests glass tubes 1½ inches in diameter and 20 inches in length were tamped full of sand, set upright, and the sand saturated by forcing oil up from the bottom. They were then drained at a temperature of 70° F. through a small glass tube at the bottom. The remaining oil was measured after drainage had become extremely slow and had practically ceased, no further loss in weight being detected in several days. If the draining had been continued over a long period possibly a little more oil would have been removed, but the experiments were carried on until a rate had been reached far beyond what was thought to represent the practical limits in oil production. The experiments were not carried to the greatest accuracy but are believed to contain no material errors. The full range of conditions found in the oil fields was not covered, and both the upper and lower limits may be exceeded, but these figures illustrate the possibilities of oil being retained in this way. The conditions of the experiments, a homogeneous mass of clean sand in an upright tube, are far more favorable for draining in almost every particular than are those ordinarily found in oil sands and suggest how much oil may be retained when gravity is the sole force for expelling the oil.

How tightly this oil is retained was shown by letting fresh water flow through the tubes of drained sand from the bottom to the top at a temperature of 70° F., for from only one tube was there even a color of oil on the water after it had passed through.

The sands experimented with were a coarse sand, having well-rounded grains of uniform size, average diameter about six two-hundred-and-fifty-fourths inch, and a porosity about 37 per cent, and a finer sand, having angular grains of irregular size, about three two-hundred-and-fifty-fourths inch average diameter, and an average porosity of 38.5 per cent.

TABLE 3.—*Quantities of oil retained in drained sands.*

Oil.	Sand.	Time drained, days.	Oil retained, percentage of capacity of sand.
Bradford crude, gravity 41.2° B. (0.818)	Coarse	26	15.0
Do	Fine	26	21.0
California crude, gravity 25.1° B. (0.903)	Coarse	42	24.0
Do	Fine	43	42.0
California crude, gravity 14° B. (0.972)	Coarse	73	30.5
Do	Fine	73	53.0

To determine how alternating layers of coarse and of fine sand affect the amount of oil retained, a tube was packed with alternating layers of such sands, saturated with oil and then allowed to drain until no further loss of weight could be detected during a period of several days. The results were compared with those obtained by using similar tubes in which only one of the sands was packed. In the fine sand alone, 21 per cent of oil was retained; with the coarse sand alone, 18 per cent; whereas with the two sands in alternating layers, 35 per cent of the oil in the tube did not drain out. No barriers were interposed between the layers in the two kinds of sand, yet much oil remained concentrated in the layers of finer sand, its superior capillary power not permitting the coarse sand below to withdraw the oil.

Other experiments indicated that the ultimate recoveries by water displacement were no greater and, indeed, appeared to be somewhat smaller than by natural drainage even under the favorable laboratory conditions. In these experiments water was allowed to rise through the tubes from the bottom to the top under various conditions of sand, oil, and pressure. Always a considerable portion of the oil displaced and flushed from the sand was accompanied by so much water that its recovery would not be feasible in the field. When the experimental conditions more nearly resembled field conditions the oil displaced, unaccompanied by water, was much less, so that the oil ultimately retained in the sand became greater. This was particularly true when the sand had been partly drained before letting the water rise through it, the water showing a marked tendency to bypass and trap the oil.

By forcing compressed air or gas through the tubes greater recoveries were obtained than by natural drainage or by water displacement. With the same oils and the same fine sand as in Table 3, only 17½ per cent of the 41.2° B. Bradford oil and 28 per cent of the 25.1° B. California oil were retained, the relative recovery being greater with the heavier oil. After all the oil possible had been removed by the air or gas, the passage of water even under 50 pounds pressure failed to remove as much as an iridescent film of oil from the sand.

At this time no general statements in regard to the efficiency of the recovery of oil under the various natural conditions can be made, except that it is generally considered to be greater in the deeper sands because pressures are generally greater; however, the smaller cost of producing from shallow wells allows them to be pumped to smaller productions, which partly compensates for the greater energy stored in the deeper sands. In small quantities salt water is generally considered to result in greater recovery in the eastern fields in sandstones producing paraffin oils, but in larger quantities it increases the cost of production and cuts short the life of the well. Where a sand is flooded with water, as in a " water drive," the water is almost certain to trap a large part of the oil. The spacing of wells also affects the recovery of oil from the sand, as well as the method of operating them. Commercial conditions are important factors, for if it were profitable to pump the well down to one-tenth of a barrel a day, as is done in some Pennsylvania fields, obviously there would be less oil left in the sand than if 10 barrels daily were the economic minimum, as for some California wells. The life of a well is terminated at the point where production ceases to be profitable, and not by the complete exhaustion of the oil.

PROPORTION OF OIL LEFT UNDERGROUND.

While it is obvious that both the proportion retained and the additional oil possible of recovery will vary under the diverse conditions in the fields of the United States, yet in the following paragraphs reasons are advanced for thinking that the usual methods of production are leaving by far the larger part of the oil underground and that a considerable part of this oil seems possible of recovery.

What percentage of the oil is retained in a sand after the wells are abandoned and how much of the retained oil is capable of commercial extraction are matters of varying opinion. Reliable estimates of the quantities of oil remaining in a field after the wells have been considered exhausted would be highly desirable, for they would demonstrate the incompleteness of the usual production methods and how much effort was warranted in devising and applying ways to increase recovery. There is much evidence showing that immense quantities of oil capable of being extracted remains underground, and probably more oil is left in the sands than is brought to the surface.

Opinions on the amount of oil left underground have ranged from 25 to 90 per cent, the commonest estimates being about 50 per cent. Precise data have never been submitted with any of the estimates, they being frankly generalities based on the judgments and experiences of the estimators. Some of the estimates are as follows: White,[a] 25 per cent for the oil sands of West Virginia: Arnold and Garfias,[b] 40 to 60 per cent for the oil sands of California; Ashburner,[c] 90 per cent for the oil sands of Pennsylvania; Dunn,[d] 25 to 85 per cent; Naramore,[e] 90 per cent; Washburne,[f] 36 to 60 per cent.

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[a] White, I. C., Petroleum and natural gas: West Virginia Geol. Survey, vol. 1, 1904, p. 46.

[b] Arnold, R., and Garfias, V. R., Methods of oil recovery in California: Tech. Paper 70, Bureau of Mines, 1914, p. 6.

[c] Ashburner, C. A., Petroleum and natural gas in New York: Trans. Am. Inst. Min. Eng., vol. 16, 1887–88, p. 915.

[d] Dunn, I. L., Statement before Corporation Commission of Oklahoma, 1915.

[e] Naramore, Chester, Personal communication.

[f] Washburne, C. W., The estimation of oil reserves: Bull. 98, Am. Inst. Min. Eng., February, 1915, pp. 469–471.

The estimate of Ashburner, made in 1887, is especially interesting: Ashburner says:

> From my own estimates, I have determined that the oil-producing sand in the Venango district up to the present time has produced an average of only 900,000 barrels of oil per square mile. It is impossible to determine the absolute thickness of the reservoir sand over any definite area, even as small as that of 1 square mile. There are so many variable factors which enter into the problem that it is difficult to arrive at any fair conclusion on the question of relative porosity. From estimates which I have made of the producing capacity of the oil and gas sands of the different Pennsylvania and New York districts, I believe that the amount of oil which will be ultimately retained by capillary attraction in the pores of the sand beds will range from eight to nine times as much as the total amount of oil which it will be possible to extract from these sands through wells.

There is much positive evidence that recoveries are far from complete. The wells are seldom entirely exhausted when abandoned, whereas wells that have been abandoned for many years have been rejuvenated and made productive again in some eastern fields by the Smith-Dunn or Marietta process and at Bradford, Pa., by water flooding. New wells drilled among old wells show that the oil is not exhausted, and in some of the older Appalachian fields a second or even a third crop of wells has been drilled. The results with the compressed-air process described herein and those with flooding at Bradford have demonstrated that much oil capable of commercial extraction remains in the fields after they have been virtually exhausted by the usual production methods. These processes, however, have not been used long enough to show just how great the increased recovery will be.

In subsequent paragraphs it is shown that the productions of the fields in the United States have been only a fraction of the capacities of the oil sands conservatively estimated. If these figures could be accepted without reservation to apply to the proportion of oil left unrecovered, the author would estimate that only 10 to 20 per cent of the oil ordinarily is extracted.

It has been shown that the commercial exhaustion of a well follows the exhaustion of the gas, and is not necessarily due to the exhaustion of the oil in the productive formation. Data derived from experiments and from facts observed in the oil fields show that much oil may be retained in the sand after the gas has been exhausted, and only the comparatively weak force of gravity remains to expel the oil. Considering these facts and bearing in mind that the decline of an oil well is coincident with the exhaustion of the gas pressure, it seems not improbable that only a minor part of the oil is brought to the surface. It is known that the gas escapes from the sand much faster than the oil and that the quantity of gas usually produced with a barrel of oil is much greater than could have been absorbed in that quantity of oil under the pressures and other conditions existing underground even when the oil sand was not connected with the gas sand.

It may be possible, by observing the quantity of gas produced with the oil during a period in the life of the wells, and the decreases in gas pressure and the changes in composition of the gas during this period, to determine from the laws of the physical relations of gases and liquids whether all or what proportion of the gas has been held in solution, and to estimate the quantity of oil underground in which it had been absorbed. So far as known to the writer, such a method has never been tried in the oil fields, but it is based upon well-known scientific laws, and it is suggested that if practically applied it might give the results desired without having to estimate the porosity, thickness, or area of the oil sand.

As shown previously by experimental data, the volume of air or of a gas necessary to expel an additional portion of the oil remaining in the sand increases tremendously with the progressive extraction of the oil from the sand. For example, it was found in certain other experiments with the same Bradford oil and fine sand, shown in Table 3, that to expel an additional per cent of the oil after some 50 per cent had already been removed, required hundreds of times greater volume of free gas (artificial gas used in San Francisco, Cal.) at the same pressure than when the sand was only 30 per cent drained, and thousands of times greater than when only 10 or 20 per cent drained. The efficiency of expulsion decreases enormously with each decrease in degree of saturation, so that the greatest actual as well as relative recovery would be obtained where the sands were fully or nearly saturated, even if more gas could be stored in the sands when less completely filled with oil. The experiments indicate that it would hardly be possible to store in the oil sands gas enough under sufficient pressure, within the limits found in the oil fields, to expel any high percentage of the oil, and that the smaller the degree of saturation the smaller the percentage of the contained oil that would be expelled. Compared with these experimental conditions the conditions in the oil sands are far less favorable; the thickness and irregularity of the sand body, as well as the greater distances the oil and gas would have to travel to the wells, all make for greater waste of the expulsive force and a general decrease in efficiency. The observed fact that much more gas accompanies the production of a barrel of oil than could be held in solution under the original well pressures is in harmony with these experimental results, and indicates that the expulsive force contained in several barrels of oil is required to expel one from the sand. For these reasons the theory of low original saturation of the oil sands sometimes advanced to explain low recoveries seems very improbable, likewise high recoveries are not to be expected, and the estimate of 80 to 90 per cent of the oil left underground does not seem incredible.

Obviously much of the oil will never be capable of commercial extraction, but what this minimum unextractable proportion may be no one can tell until further efforts have been made to increase recovery. It has been customary for the operators to accept the natural decline and commercial exhaustion of their wells without question or further efforts to see whether it was the oil itself or the forces in the sand that were exhausted and there is no reason to believe that both are exhausted at the same time. The truth seems to be that the natural forces in the oil sands are sufficient to expel only a small portion of the oil and that much of the remaining oil is capable of recovery if new forces are applied.

CAPACITIES OF OIL SANDS.

From the evidence previously submitted the following figures on the porosities of oil sands are believed to be reasonable. The porosities of oil sands are much greater than the uninformed would suspect from a casual inspection of specimens, whereas the usual ways of testing the porosity lead to underestimates. There is little published information on the porosities of sands actually productive of gas or oil, but there is no reason to believe that they are less than for other sands and sandstones. Indeed, as pointed out previously, the porosities of the oil-producing sandstones of the Mid-Continent and eastern fields must be greater than the figures on the building sandstones indicate. In any event, the recovery of gas shows that the estimated capacities of the oil sands, as given in the following table, can not be in gross error.

Estimated average capacities of oil sands.

	Estimated average porosity, per cent.	Capacity per acre-foot, barrels.
Appalachian field	12½	970
Illinois and Mid-Continent fields	17½	1,358
California fields	25	1,940

ACTUAL RECOVERY FROM OIL AND GAS SANDS.

According to the United States Geological Survey,[a] 3,335.457,140 barrels of oil have been marketed from 329,186 oil wells in the United States up to the beginning of 1915. During 1914, 265,762,535 barrels were marketed from 179,129 oil wells. It is estimated that the average well drained about 6 acres of oil land, the total area being about 2,000,000 acres. The future production for the wells producing in 1914 is estimated to be not more than 1,400,000,000 barrels, making a total production of approximately 4,700,000,000 barrels, or approximately 2,350 barrels per acre, which is hardly enough to saturate an oil sand 2 feet thick of average porosity.

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[a] Northrup, J. D., Petroleum: Mineral Resources U. S. for 1914, U. S. Geol. Survey, 1915, p. 889.

Statistics by the United States Geological Survey[a] show that 591,866,733,000 cubic feet of natural gas was produced and used in the United States in 1914, which does not include the enormous wastage. The average pressure being approximately 250 pounds at the well, the space occupied would be equivalent to some 5,850,000,000 barrels of oil, which is nearly double the total oil production and is twenty-two times the oil production for 1914. If 40 acres be allowed for each gas well producing in 1914, the area of gas-producing sands was about 1,400,000 acres, which is not as much as the total oil-producing sand. This gas was produced from sands which yield oil in the same districts, and there is no evidence that their capacities are greater than for oil sands. Similar comparisons for former years show even greater discrepancies between the spaces occupied by the oil and gas.

Day,[b] in 1907, estimated the recovery from the Appalachian fields to have been less than 800 barrels per acre. On this basis the total recovery will not exceed 1,000 barrels per acre, or only enough to saturate an oil sand 1 foot thick with a porosity of 12½ per cent. White[c] has estimated the average thickness of the pay streaks alone to be 5 feet in West Virginia. This is undoubtedly a conservative estimate when applied to the whole Appalachian fields.

From available records the production of the Bradford field,[d] in Pennsylvania, has been about 230,000,000 barrels. The area of the field is said to be approximately 85,000 acres.[e] The average well production is now but a small fraction of a barrel daily, so that the field may be considered practically exhausted, yet the total production has approximated only 2,700 barrels per acre, or not enough to saturate 3 feet of sand, although the sand is reported to average 45 feet thick and to be oil bearing and comparatively uniform throughout.

The marketed oil production of Illinois to 1915 has been 232,326,616 barrels from 19,808 wells. In 1914 the marketed production was

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[a] Northrup, J. D., Natural gas: Mineral Resources U. S. for 1914, U. S. Geol. Survey, 1915, p. 749.

[b] Day, D. T., Petroleum resources of the United States: Bull. 394, U. S. Geol. Survey, 1909, p. 34.

[c] White, I. C., Petroleum and natural gas: West Virginia Geol. Survey, Vol. I, 1904, p. 46.

[d] Compiled from statistics of Second Geographical Survey of Pennsylvania, vol. 10; U. S. Census Report; and annual volumes of Mineral Resources of United States, U. S. Geol. Survey. Productions for 1885–1887, 1890, 1907–1914 are estimated.

[e] Ashburner, C. A., Second U. S. Census Report, p. 432.

21,919,749 barrels from 14,800 wells, whose future production is estimated to be about 100,000,000 barrels, or a total of about 330,000,000 barrels. Assuming a drainage area of about 6 acres per well, each acre will contribute about 2,750 barrels, which would saturate an oil sand 2 feet thick of 17½ per cent porosity, yet the thickness of the "pay streaks" in the average well of Illinois has been estimated to approximate 25 feet.[a]

The total oil marketed from Oklahoma up to 1915 has been about 462,000,000 barrels, to which 38,875 wells have contributed. The marketed production in 1914 was 73,631,724 barrels from 27,794 wells, and the future production can be reasonably estimated not to exceed 300,000,000 barrels, a total of 762,000,000 barrels. From a record of over 6,000 wells on the lands of restricted Indians[b] it is found that there is on the average one well to each 5.7 acres, at which figure the total producing acreage in Oklahoma is not over 225,000 acres, and the production per acre will approximate 3,400 barrels, which would not saturate 3 feet of sand of the estimated porosity, although the average thickness of the oil sands in Oklahoma is many times greater.

A large gas company operating in northeastern Oklahoma estimates from its experience that the marketed production from an average gas well in that district is about 300,000,000 cubic feet.[c] This does not include the enormous wastage or the gas left underground. The average original pressure in the gas fields in this part of the State would be about 600 pounds, or, roughly, 40 atmospheres, and there would be an average of one gas well to 40 acres of gas land. From these figures it is calculated that the gas must have come from sands which average 24 feet in thickness and would contain 33,500 barrels per acre, or ten times the thickness of sand indicated by the recovery of oil. The gas is produced from sands that are oil bearing near by.

McLaughlin[d] states that the recovery from the Kern River field, in California, has been approximately 26,000 barrels per acre to 1915. As the field has been producing for 14 years, and is nearly drilled up, an optimistic estimate of the future production would make the total recovery not more than 40,000 barrels per acre, or enough to saturate about 20 feet of sand, whereas a thickness of 200 to 300 feet is reported in that field. McLaughlin also reports actual recoveries from a number of properties in the Midway and Coalinga fields, California, from which the following tabulation has been made:[a]

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[a] Day, D. T., Petroleum resources of the United States: Bull. 394, U. S. Geol. Survey, 1909, p. 34.

[b] Second annual report United States oil and gas inspector for the Five Civilized Tribes, 1915.

[c] Personal communication from A. J. Deischer, of Bartlesville, Okla.

[d] McLaughlin, R. P., Petroleum industry of California: Bull. 69, State Mining Bureau, 1914, p. 204.

Recoveries from the Coalinga and Midway fields, California.

[Adapted from data by R. P. McLaughlin.]

	Coalinga.	Midway.
Number of properties	13	18
Average thicknesses of oil sands, feet	96	90
Average production per acre, barrels	22,012	13,579
Average age of well, years	6	4
Average production per acre-foot, barrels	222.5	151
Average recovery,[b] per cent	11.5	7.8
Minimum production per acre-foot, barrels	26.5	51
Minimum recovery,[b] per cent	1.4	2.6
Maximum production per acre-foot, barrels	838	742
Maximum recovery,[b] per cent	43.3	38.2

These properties are still producing but have yielded at least two-thirds of their total production. The figures show that the recovery will average not more than 15 to 20 per cent of the assumed porosity of 25 per cent. The difference in individual yields is noteworthy and can not be explained by relative skill in operating the wells but is due mostly to natural conditions. Undoubtedly there are considerable variations in the porosities of the sands and also errors in estimating their thicknesses and the areas of drainage, but these facts can not fully reconcile the extremes of recovery of 1.4 per cent and 43.3 per cent shown in the table. Occasionally the recovery from individual wells or small properties is very high, and at times it is difficult to explain how so much oil could be obtained from these properties, but almost invariably such high recovery is from the first wells drilled in a field of high pressure, and undoubtedly a much larger area has contributed to the yield than has been figured. These high extremes have led many engineers to overestimate the future recoveries from oil fields, but when the entire field is considered it will be found that the average recoveries are low and that the high recoveries are abnormal and very rare.

Although the estimates given are only approximate, there can be no reason for doubting, after fair deductions have been made for errors and overestimates, that ordinarily the oil produced represents only a small part of the capacity of the sand. The differences between recovery and capacity are so large that few possible sources of error or other factors could reconcile them. The estimated capacities of the oil sands are within reasonable accord with the recoveries of gas from continuations of the same sand beds in the same districts, and there are no reasons known why their average porosities and thicknesses should be less where oil bearing. The quantities of gas produced with the oil, where the gas is known to come only from oil-producing sands, indicate that the capacity of the oil sands is much greater than the volume of oil recovered, and hence either the recovery is very small or a large part of the pore space is occupied by free undissolved gas mechanically entangled with the oil. In the writer's opinion a solution of this problem would determine whether the recoveries made actually approximate only a fifth or tenth part of the oil in the sand. The experiments show that an excess of gas is to be expected with the oil even if the sand is fully saturated and that with partial saturation an even larger percentage of the oil contained in the sand can be expected to be left underground. In any event the efforts so far made to increase recovery show that enough more oil could be brought to the surface by applying additional pressure in the sand to make such efforts worth while.

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[a] McLaughlin, R. P., work cited.

[b] Twenty-five per cent porosity and complete saturation assumed.

USE OF GAS PUMPS FOR INCREASING PRODUCTION OF OIL WELLS.

Vacuum or gas pumps, according to Carll,[a] were first employed in the old Triumph pool, Pennsylvania, in 1869. Their use gradually increased in the Appalachian fields, and during the past 10 years they have been employed extensively throughout the Mid-Continent fields and the fields east of the Mississippi River.

The effect of the gas pump is twofold. It increases the yield of oil and the quantity and richness of the gas. Its effect on the gas production has had a marked influence on the condensation of gasoline from casing-head gas by compression, and many gasoline plants would not be in use to-day except for the gas pumps. On the other hand, gas pumps would not be used so extensively were it not for the natural-gas gasoline plants, for experience has shown that gas pumps are seldom profitable from the increase of oil production alone. The benefits of increasing the oil production are short lived, and are accompanied by much extra trouble and expense.

It has been shown that reduction of pressure in an oil sand releases more gas from solution and permits greater expansion of the gas. Samples of oil several years old will froth and become lively when subjected to a few pounds of negative pressure showing how gas and vapors are liberated at reduced pressures. Consequently reducing the pressure at the well below atmospheric by a gas pump provides additional expulsive forces in the sand not available before. The theoretical vacuum limit of gas pumps is −14.7 pounds per square inch at sea level, and less at higher elevations. It has been claimed that a vacuum of −13 pounds has been reached in actual practice. Gas pumps are placed on wells after the production has declined to a very small figure and the gas has nearly reached atmospheric pressure; hence the reduction of pressure ordinarily effected by the gas pump is not more than 15 or 20 pounds per square inch. As the effectiveness of the gas pump depends principally upon the gases released in the oil sand by the reduced pressure, the limit of its usefulness is reached when these gases are exhausted from the sand, unless air or natural gas is allowed to enter the sand, and is sucked through by the gas pump. Results of sucking air through the sand should be practically the same as forcing air through the sand at positive pressures of not more than 13 pounds. It is obvious that when the natural gas accompanying the oil has been exhausted the practical limit of efficiency of the gas pumps has been reached so far as increasing the production of oil is concerned.

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[a] Carll, J. F., Seventh report on the oil and gas fields of western Pennsylvania: Second Geol. Survey of Pennsylvania, 1890, pp. 12–13.

Gas pumps are not employed until the wells have reached low pressures and small productions. Usually the production of oil is increased, sometimes it is doubled or trebled, but this favorable effect seldom lasts long, and in a few years the production drops to or below the former level. Figures 11, 12, and 13 (see pp. 68–69) show the effects of the use of gas pumps on the productions from certain properties, and also how inadequate the method is for extracting all the oil in the sand. It is not claimed, however, that these properties represent a fair average for the benefits derived from gas pumping.

Gas pumping considerably increases the cost of producing oil, and this increase is not often compensated by the extra profits derived from the increase of oil production alone. Considerable equipment must be invested in and attended to, as the method requires a gas engine, suction pump with housing and accessories, and suction lines extended to every well, while each well must be packed tightly. The suction in the well often causes the walls to cave, or increases the amount of floating sand and silt coming in with the oil so that casings must be pulled oftener, and the wear on pumping apparatus is much greater. While the well is being "pulled," the air rushes into the sand and drives the oil away from the hole, and there being no gas pressure in the sand to force the oil back it may be many days after the well is put back on the suction line before the oil is brought back to the hole. During this time the well is a nonproducer so that although the daily yield may be increased during the time the wells are actually pumped, the production over a longer period is likely to prove disappointing. This loss of time, and the expense of "pulling the wells" and of keeping up the plant, is apt to more than counterbalance benefits derived from the increase in production, as it is temporary and seldom lasts more than 3 or 4 years. Once the property has been gas pumped, however, experience shows that usually pumping at negative pressures can not be discontinued, because the air rushing into the sand drives the oil away from the well and makes it almost impossible to obtain profitable production again by ordinary methods, hence gas pumping must be continued long after the benefits from it have ceased. The writer believes, however, this evil effect can be lessened by letting the air into the sand very gradually and thus reducing the force of the inrushing air.

After most of the gas in the oil sand has been removed and the pressure reduced below atmospheric, gravitational drainage and possibly water flushing are the only motive forces left to move the oil from the sand. How little effect gravity alone has upon the movement of the oil is shown by the fact that the production practically ceases when gas pumping is stopped after the pressure in the well has been reduced below atmospheric. The oil does not flow into the wells when the flow of the small volume of gas caused by the suction ceases. Carll[a] in speaking of conditions in the Triumph pool, Pennsylvania, after gas pumping had been continued until there were negative pressures of —12 pounds in the oil sand, says:

> New wells are occasionally drilled on this exhausted belt, and it invariably happens that when this oil sand is pierced a current of air commences to whistle down the hole, nor can any oil be obtained till the well mouth is closed and a gas pump put in operation. After a few days' testing, oil begins to appear and the production frequently runs up to 15 to 20 barrels per day. Then, as the slight excess of fluid in the immediate vicinity of the hole drains, and an equilibrium is established, the output gradually shrinks to the level of the old wells in the pool.

Although the use of gas pumps is seldom justified by the increase of oil production, it frequently becomes profitable, as formerly stated, through the gasoline derived from the gas. Probably the majority of casing-head gasoline compressor plants in the Mid-Continent fields and the fields east of the Mississippi River use gas from gas-pumped wells, and this is often extraordinarily rich in gasoline vapors. To a considerable extent the casing-head gasoline production, which has reached enormous proportions in recent years, is dependent upon gas pumping. The recent high prices of gasoline have greatly stimulated the installation of gas pumps, and made the process profitable where heretofore it was not. The process is considered to be especially profitable in some of the Oklahoma fields.

The use of gas pumps has in the past been generally condemned by producers upon the ground that it seldom pays, but inquiries have failed to disclose opinions that the process injures the sand. In the writer's opinion it may possibly aggravate water troubles by lowering the pressure in the sand, but otherwise he has no facts showing it to be seriously injurious.

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[a] Carll, J. F., Seventh report on the oil and gas fields of western Pennsylvania: Second Geol. Survey of Pennsylvania, 1890, pp. 12–13.

One motive for installing gas pumps has been to draw production from adjoining properties. As the pressures are lower at wells being gas pumped, the gas in the district tends to flow toward those wells, and the areas drained by the wells are correspondingly increased. If an operator can install gas pumps before his neighbors, he gains a certain advantage, and they consider that they must install pumps on their own wells to overcome this advantage. This fact is one of the chief objections that have been raised against its use. Once gas pumping is started in a field, its use is apt to extend to all other properties.

It is believed the effect of gas pumping upon oil production of neighboring properties has probably been overestimated, though where the gas is the consideration the effect is of undoubted importance.

The effects of gas pumping may be summarized as follows: It temporarily increases production, but likewise increases expenses and operating troubles correspondingly, so that it seldom pays except where profits are derived from an increase in the volume and richness of the gas. The method hastens the recovery of the oil, but the total recovery is only slightly more than that by ordinary pumping methods.

SMITH-DUNN OR MARIETTA COMPRESSED-AIR PROCESS.

HISTORY OF PROCESS.[a]

The present successful practice of stimulating the production from oil wells by forcing air through the oil sand was started on the Wood farm of the Cumberland Oil Co., near Chesterhill, Ohio, by I. L. Dunn, in August, 1911. However valid the claims of others for priority in idea and application may be, the fact remains that the now extensive use of this method can be traced back to this first successful demonstration. With the aid of Orton C. Dunn and Harvey E. Smith, the details of practical operation were worked out and demonstrated to other oil producers. Because Messrs. Smith and Dunn have been credited with bringing the method into successful public use, the process has become known as the Smith-Dunn process, though it is also called the Marietta process because of its first extensive use near Marietta, Ohio.

Mr. I. L. Dunn states that his idea originated when operating in the Macksburg pool, Ohio, in 1903, when gas at a pressure of 45 pounds was forced into an oil well producing from the 500-foot sand. After 10 days the gas pressure was released and the well began to pump much oil, which continued till the gas had worked out again. In 1911 the experiments on the Wood farm were started. About 150,000 cubic feet of free air was compressed and forced into one well daily, at a pressure of 40 pounds, and within a week the production of the surrounding wells had increased, after which the use of compressed air was extended to other parts of the property. The Wood farm is located in the "Chesterhill streak," production being obtained from the First Cow Run sand at depths averaging about 450 feet. This property had been drilled in 1898 and had been gas pumped for several years. At the time the experiment was started, the production had dropped to an average of 7 gallons per well daily. The oil is of paraffin base, has a gravity of more than 40° B., and the sand is coarse and pebbly. The effect of the process on this property is shown in figure 11 (see p. 68).

The process is known to have been employed on over 90 properties, of which at least 80 per cent have been successful. Nearly all of these properties are located in the Appalachian fields in the southeastern parts of Ohio and the northwestern parts of West Virginia. Probably 4,000 wells have been affected by the process, and its use is extending rapidly, being retarded principally by the difficulty in obtaining machinery under the present abnormal conditions. Few of the plants are more than three years old, and probably half the plants were installed during the past year (1916). It was not until recently that the producers in the district became fully awakened as to what was being accomplished, and as to how much oil still remains underground. The recent expansion in the use of this process is sufficient warrant of its practicability and success.

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[a] The principle of increasing production by forcing air or any other gas through the oil sand, and many details of operation, are covered by U. S. patents controlled mostly by I. L. Dunn, of Marietta, Ohio, and others. See Oil and Gas Journal, vol. 15, No. 4, June 29, 1916, p. 34.

PRINCIPLES OF PROCESS.

The essential principle of the Smith-Dunn or Marietta process is to replace the natural gas, which originally accompanied the oil and was the principal agent in forcing the oil into the wells but has been exhausted, with compressed air. The air is forced into the sand under pressures varying from 40 to 300 pounds through some of the wells on the property, which are called "air wells," the oil being pumped from the other wells in the usual way. Any gas which does not combine with the oil chemically under the conditions existing underground could be used, but of these gases only air and natural gas are practically available. On the old, nearly exhausted properties where the process has been employed natural gas is seldom available, or only at excessive costs, and it is seldom practicable to use anything but air.

PROCEDURE IN INSTALLING PROCESS.

EQUIPMENT REQUIRED.

The extra equipment necessary for using the process over that commonly used on any producing oil lease consists of an air-compressor plant, a system of piping for conveying the compressed air to the air wells, and the preparation of certain wells for taking air.

The air compressor can be of any efficient type, and is usually driven by a gas engine, because gas is in nearly every instance the cheapest and most available fuel. However, any other type of engine can be employed. The tendency has been toward using direct-driven types because of greater efficiency and compactness.

The compressors in use vary in size from 20 to 100 horsepower. It is considered advisable to restrict the size of the units to 100 horsepower, and where more power is needed to install additional units. Where the air is compressed to a pressure of more than 100 pounds, two-stage compressors are generally used. Some operators recommend that 80 pounds is the better maximum for single-stage compressors. Information on compressors used at 42 properties, with various other data, are presented in Table 4.

TABLE 4.—*Conditions on 42 properties using the Smith-Dunn or Marietta process.*

Number of property.	Name of oil sand.	Texture of sand.	Approximate average depth of wells, feet.	Number of wells on property.		Age of wells, years.	Previously gas pumped.	Rated horse-power of compressor.	Rated horse-power per well.	Approximate air pressure used, pounds per square inch.
				All wells.	Air wells.					
1	First Cow Run	Coarse	450	108	28	18	Yes	90	0.83	45
2	do	do	700	58	19	13	Yes	150	2.6	70
3	do	do	400	27	7	20	Yes	40	1.5	45
4	do	do	80–120	100	35	20–55	Yes	150	1.5	40
5	Macksburg 500	Medium	500–700	19	6	55	No	35	1.8	110
6	First Cow Run	do	600	32	9	16	Yes	40	1.25	50
7	do	Coarse	80–400	140	40	20–55	Yes	185	1.3	55
8	Rosenberry	Coarse and fine (or stray sand).	1,300	91	21	24	Yes	180	2.0	70
9	First Cow Run	Medium	250	16	5	11–13	Yes	20	1.25	45
10	do	do	700	28	8	16	Yes	75	2.7	70
11	Peeker	Fine, slaty	350	93	32	12	No	100	1.1	240
12	Macksburg 500	Fine	700	32	7	26	No	75	2.45	60
13	First Cow Run	Medium	800	100	23	20–50	No	100	1.0	130
14	do	Coarse	120–400	78	28	16	Yes	100	1.3	45
15	do	Fine and coarse	400	17	5	16	Yes	40	2.35	70
16	do	Fine	500–800	17		9	No	45	2.65	160
17	Third Venango	Fine and tight	900	65	20	40	No	85	1.3	320
18	Bartlesville	Fine and slaty	500	80	13		No	100	1.25	300
19	First Cow Run	Coarse	250	83	31	12–55	Yes	*a* 120	1.55	125
20	Buell Run	Medium	400	16	3	10	No	40	2.5	100
21	Salt	Coarse	1,800–2,000	26	5	15	No	85	3.3	200
22	First Cow Run	Fine	500–700	16	4	11	No	35	2.2	160
23	do	Medium	700							60
24	Berea	Fine	1,800	17	3	25	No	20	1.2	200
25	First Cow Run	Medium	200	40	10	20	No	40	1.0	50
26	do	do	800	23	7	16	Yes	50	2.2	70
27	do	do	400	28	7	4–16	Yes	25	.9	45
28	do	Fine and coarse	700–800	78	11	12	No	100	1.3	160–235
29	Second Venango	Fine	1,400							270
30	Macksburg 500	do	900	12	4	20	No	25	2.1	140
31	Mitchel	Medium	400–500	40	12	21	No	65	1.5	90
32	First Cow Run	Coarse	300	12	3	12	No	20	1.7	100
33	do	do	400–500	16	7	2–6	No	*b* 75	4.7	120
34	do		Shallow.	6	3					100
35	do		Shallow.	4	1	6	No			100

36	.....do.		400	28	4	6				
37	.....do.		Shallow.	6	2					100
38	.....do.			40		12	No.	90	2.25	90
39	.....do.							60		55
40	Keener	Coarse	1,700-2,300							60
41	Big Injun		2,300-2,500							200
42	Bradford	Medium	1,800-2,000		1		No.			80
	Total or average			1,592	424			74½	1.83	1.15

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[a] Engines also used to pump wells.

[b] Air being supplied to other properties.

On account of having to use gas diluted with air, it is frequently necessary to enlarge the gas intake and reduce the air intake correspondingly. Gas engines are now being constructed which are fitted with special valves for regulating the gas and air intakes conveniently.

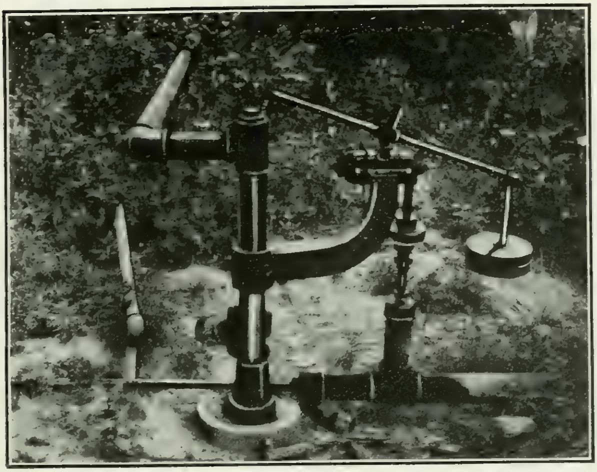
The compressor plant should be situated convenient to an adequate water supply, because considerable water is needed to cool the engine and the compressor. The site of the plant should also be selected with a view to distributing the air with a minimum amount of pipe, as this item will comprise a considerable part of the initial cost of installing the process. Moreover, the farther the air has to travel through pipes the greater is the loss of volume and pressure from leakage and friction. On large properties it is considered the better policy to put in several plants rather than to build large central stations.

The compressed air is distributed through 2-inch to 4-inch mains, with 1-inch laterals leading to the air wells. With the distances and the velocities of air used on the ordinary plant, these sizes are large enough and the pressure losses due to friction do not warrant the extra cost of increasing the size of the pipe. The air should be conducted through a cooling system near the compressor (see Pl. I, *B*) and the water drained off in traps, otherwise it will give trouble in the lines, especially in winter.

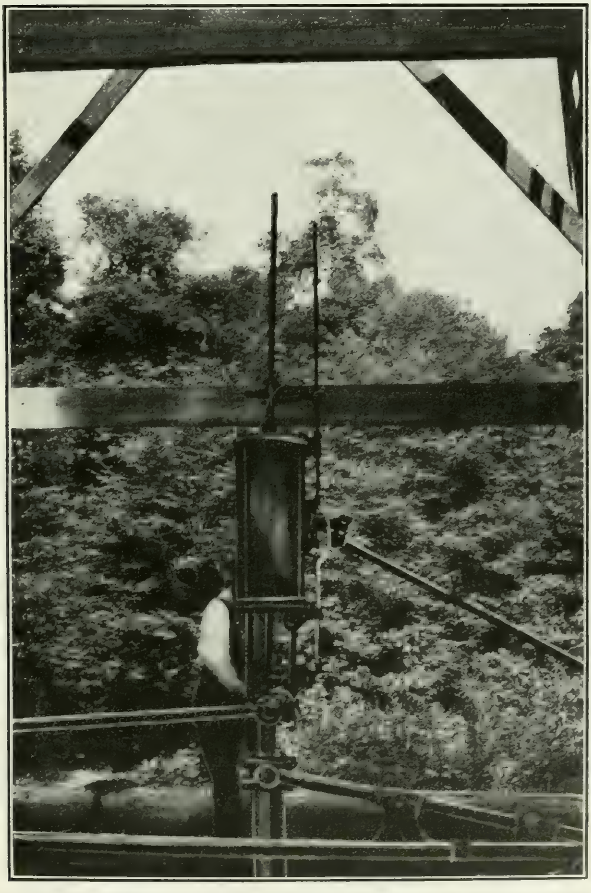
It is also necessary to have a gas-gathering system from the pumping wells to supply fuel for the compressor plant. These usually consist of 2-inch lines, and the system is essentially the same as on the ordinary lease where casing-head gas is used for fuel or for making gasoline.

The well-pumping equipment can be of the usual kinds, but as the compressed air can be used as a source of power there has been a tendency to put in pumps operated by compressed air. Plates III and IV, *A*, show types of such pumping equipment. The pumps shown in Plate III, *A*, operate on the displacement principle, whereas in the equipment shown in Plate III, *B*, the compressed air is used as in a steam cylinder, the sucker rods being attached to the piston rod. By using compressed air, the engine, pumping power, and housing can be done away with, as well as the shackle rods and the jacks. It is used at Bradford in pump heads (see Pl. III, *B*) and in modified steam engines (see Pl. IV, *A*), because there is not so much loss of power in transmission as with steam, especially in cold weather. Where compressed air is used on a lease, it can be used as a source of power for nearly every purpose.

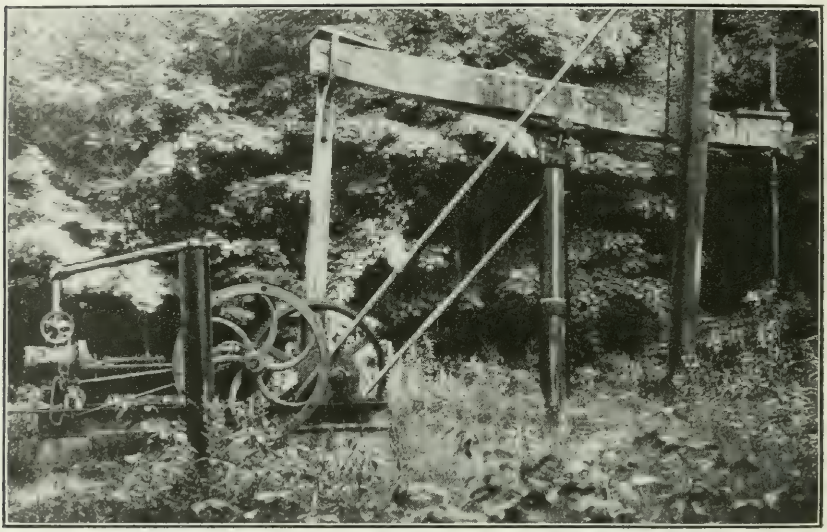
The oil-gathering equipments are of the usual kinds, and the only effect that the use of compressed air has is to reduce the number of



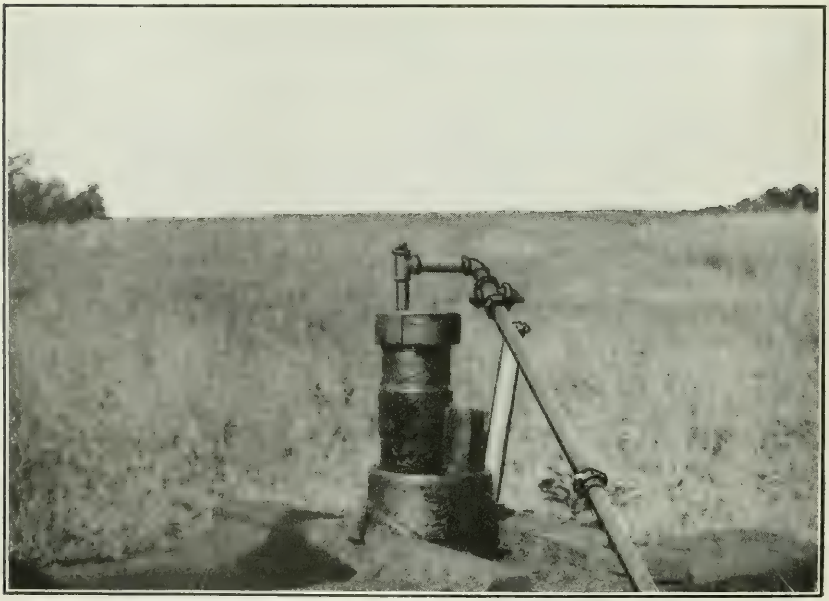
A. OIL PUMP RUN BY COMPRESSED AIR. IN USE ON A PROPERTY NEAR MALTA, OHIO.



B. "PUMP HEAD," RUN BY COMPRESSED AIR, ON PROPERTY IN THE BRADFORD FIELD WHERE FLOODING IS GOING ON.



A. PUMPING A WELL "ON THE BEAM," IN THE BRADFORD FIELD, WITH BARCROFT PUMPING GEAR RUN BY COMPRESSED AIR.



B. WELL EQUIPPED FOR TAKING COMPRESSED AIR.

pumping wells and, therefore, the amount of such equipment necessary.

The essential equipment in an air well consists of 1-inch or 2-inch piping or tubing which extends down to the top of the oil sand and is packed or cemented directly above the sand (see fig. 3). If the well is cased directly above the sand the air may be introduced through the casing (see Pl. IV, *B*). Where the pumping wells are fitted to take back pressure it is necessary that provision be taken, as in air wells, to prevent the waste of air, and, in fact, the possibility of leakage should be carefully considered at all points in the system because leaks in the air lines or the diffusion of the air into unprotected formations through air wells, pumping wells, or old abandoned wells will greatly reduce the efficiency of the method. The same can be said of the pumping equipment, and steps should be taken to prevent the unnecessary escape of air from pumping wells.

DETERMINING THE SIZE OF COMPRESSOR PLANT.

The compressor plants in use at the present time average about 75 horsepower and are operated at average pressures of about 115 pounds. The smallest plant known to

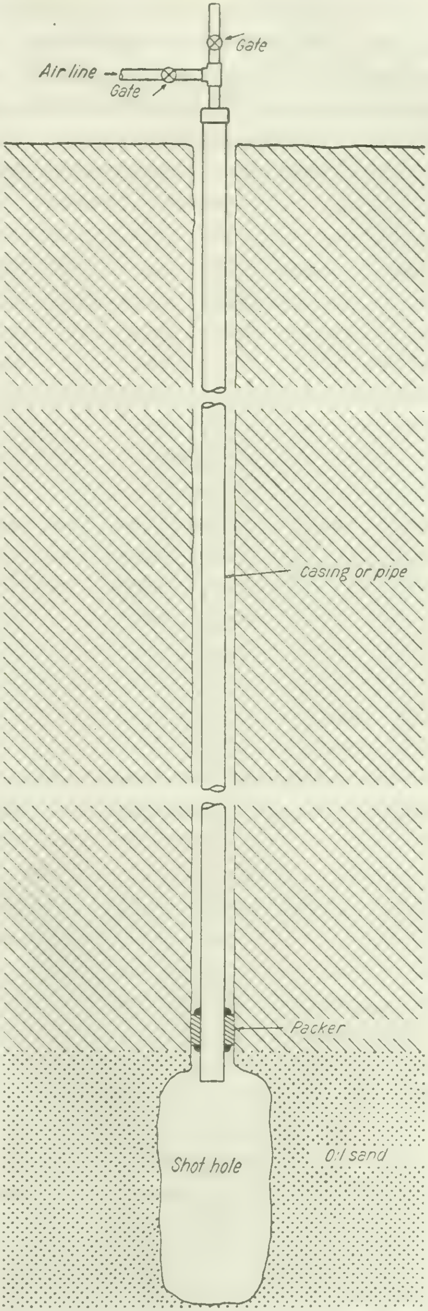


FIG. 3.—Diagram of a shallow well equipped for taking compressed air.

the writer is 20 horsepower, and the largest is 185 horsepower. The size of plant necessary will depend on the number of wells on the property, the pressures employed, and the capacity of the oil sand for taking air. Thirty-two of the plants listed in Table 4 average 1.83 horsepower per well (air and pumping wells). The lowest figure is 0.83 horsepower per well and the highest 4.7. The latter plant provides air for other properties. About the same horsepower per well is used for the different pressures (see fig. 9).

In determining the size of a plant consideration should be given to the experience gained on properties with similar conditions, especially those near by, but on account of the variations in the nature of the oil sands, even from one well to another, it is always advisable to make tests, although data on results obtained on properties near by may be available. The usual method of making such tests has been by means of a portable compressor, one of 5 horsepower having been found to be effective in the Appalachian fields. Each prospective air well is tested separately, and the volume of free air which it will take under different pressures is determined. Nearly always the sand will take practically no air until a certain minimum pressure has been exceeded, which is an indication of the frictional resistance in the sand. Also, the maximum pressure at which the sand will take all the air the testing plant can deliver at that pressure may be determined. By these tests data are obtained on the volumes and pressures the wells will require, from which the size of the plant can be estimated. It is, of course, impossible to make the calculation precise, and during the life of a property conditions may change which will modify the first estimates. As a matter of policy it is advisable to put in a larger compressor than is seemingly necessary, in order that there may be reserve power for using higher pressures and larger volumes if found desirable. The plant also decreases in efficiency with continued use, and if the gas becomes lean the actual delivery of horsepower from the gas engine becomes less.

In testing a well the capacity of the testing plant must be known, and the internal capacity of the well itself must be estimated from the size of the casing in the well and the probable size of the shot hole. At frequent intervals careful records are taken of the pressures and the rate at which the well is taking air, so that it can be computed what pressures will be necessary to force a given volume of air into the sand or how much air can be forced into the sand at given pressures. When the test is completed the response of the well to the returning air upon reduction of pressure is noted, and if the air brings back considerable oil it is considered a good indication that conditions are favorable for using the process. This, however, is not a decisive test.

When the tests have been completed they will show what volume of air each well will take at various pressures. The plant should be large enough to force into the sand the volumes of air experience has shown to be desirable. An average of about 10,000 cubic feet of free air per day is used for each well (air and pumping wells), but the volumes required are less for pressures higher than the average pressure (115 pounds) and greater for pressures lower than the average, and may be as much as 20,000 cubic feet per well daily. If the 5-horsepower portable tester showed that the wells which were to be used for taking air each averaged 40,000 cubic feet of air per day at a pressure of 120 pounds and there were to be three pumping wells for each air well, then the average volume required would be 10,000 cubic feet per well, which is the average volume for that pressure. The property would consequently require a plant of not less than 1.25 horsepower per well, and to this figure should be added a factor for reserve power. If there were to be four pumping wells to each air well, higher pressures and greater horsepower per well would be required to force in the same quantity of free air.

PREPARING AIR WELLS.

One of the most important considerations in preparing wells for taking air is not to let the air have access to any formations other than the oil sands, otherwise large quantities of air may escape into the barren strata and be wasted. The reasons for this statement are discussed in more detail in another part of this paper. If the well has a string of casing tightly seated on the top of the oil sand, the air can be let into the top of the casing through a tight head or cap (see Pl. IV, *B*). When the well is not cased in this manner, a string of small pipe or tubing is placed in the well and packed at the top of the sand, as shown in figure 3. One-inch pipe has been used in shallow fields, this sometimes being the only pipe in the hole. Considerable strength is required in the packer to withstand the upward pressure from the compressed air. The usual rubber packers frequently will not hold tight under the pressures employed, and other methods for packing must then be used.

A method of packing that has proved satisfactory for shallow wells is to wrap the pipe with broad strips of burlap or canvas, which is split at the top to form a flare, until the wrapping nearly fills the hole or the casing. The pipe is lowered into the hole to the desired position, some sand is dropped in between the pipe and the walls of the hole to flare out the burlap, and a thin mixture of sand and cement (1 to 1) is poured down outside of the pipe onto the burlap, forming a bridge 5 to 10 feet deep between the pipe and the walls of the hole, so that the pipe is securely packed when the mixture sets. The burlap is wrapped onto a short joint of pipe which has a left-hand thread at the top, and no anchor is put on the bottom of the pipe. If it is desired to remove the packing, the pipe is unscrewed at the left-hand thread, and the cement drilled out. The first few blows of the tools will probably drive the short joint of pipe through the cement and the hole can be cleared without much effort.

It has not often been considered necessary to shoot the air wells. They should, however, be cleaned out, and sometimes it is advisable to remove the waxy sediments that clog the surface of the sand. Newly drilled wells have the advantage of the sand being perfectly clean and free from waxy sediment.

Occasionally a combination well is made by forcing the air down between the casing and tubing in a pumping well. Such a well can be used as an air well for a time and then be pumped when the air is stopped and the oil comes back under the released pressure.

PREPARING PUMPING WELLS.

In preparing the wells on a property for the use of compressed air, ordinarily no changes need be made in a pumping equipment unless it is old and out of repair. However, the process is frequently installed on properties where the equipment has been allowed to run down because the small profits have not permitted repairs and replacements. Such equipment may not prove adequate to handle the increased production, nor the floating sand which often gives trouble during the first months or years that the process is used. It is also desirable to clean the wells and to put them in condition to yield the maximum production with the least pump trouble and expense. If the application of the process is successful, the additional profits will more than compensate these extra expenditures. Those operators who have spent extra time and money cleaning their wells have usually been repaid by less pumping troubles.

It is sometimes desirable to maintain back pressures in the pumping wells on the oil sand. There are several ways of preparing a well for the use of regulated back pressure, the simplest being to place a reducing valve on the gas-gathering line from the casing head. When pressure is maintained in the well by this means, the formations overlying the oil sand should be cased off so that the gas will not waste in the same way as it would in an air well not cased off. Another method for maintaining back pressures in the wells is shown in figure 4. The tubing ring used with this method is shown in figure 5.

Although the process does not require changing the type of pumping equipment, a logical development will be a greater use of com-

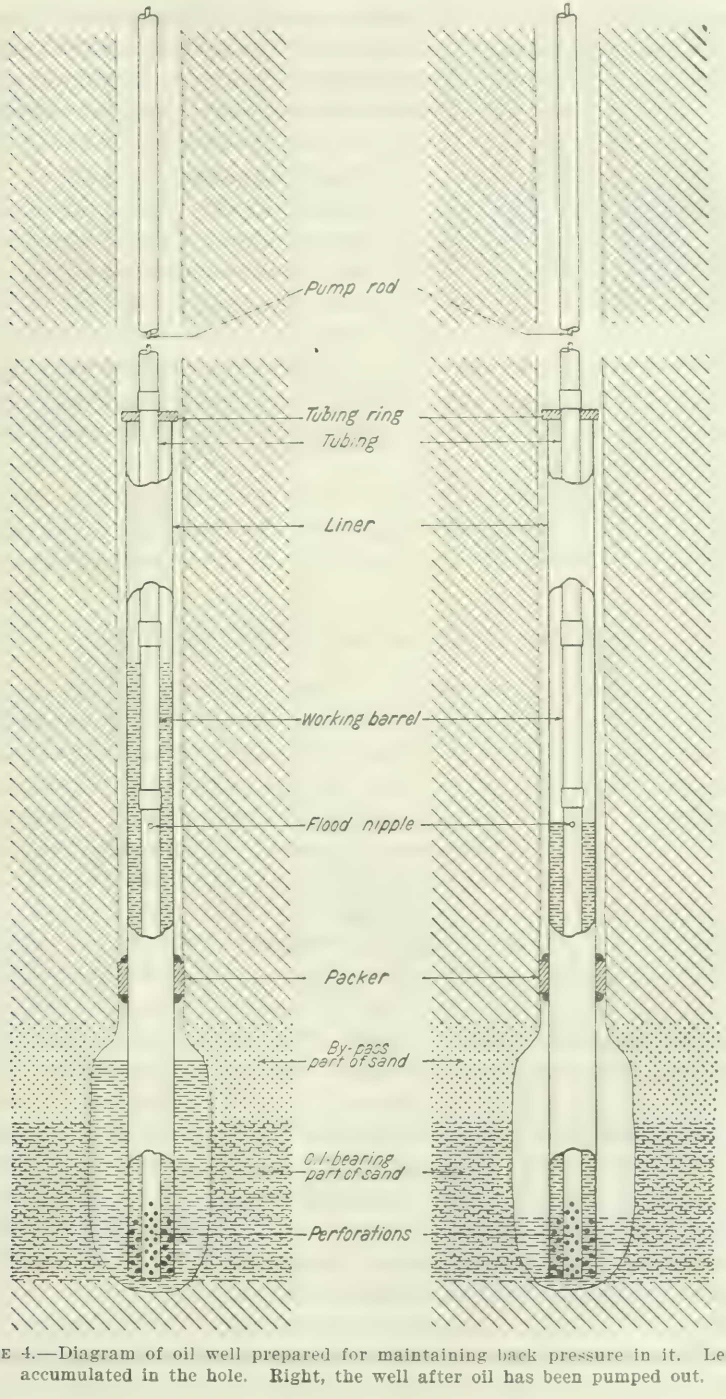


FIGURE 4.—Diagram of oil well prepared for maintaining back pressure in it. Left, oil accumulated in the hole. Right, the well after oil has been pumped out.

pressed air in the future as the source of pumping power on leases employing the process. The power is centralized, and the air is readily distributed without much loss in power, or trouble in operation. In many eastern fields the wells were pumped by compressed air long before the process of forcing compressed air into the sands came into use. At Bradford, Pa., the compressed air is also used to run steam engines, pumping wells "on the beam" (see Pl. IV, *A*), or in "air heads" (see Pl. III, *B*). Air lifts have been tried in the eastern fields but were never satisfactory. Smith and Dunn use air displacement pumps on many of the shallow wells (see Pl. III, *A*) where the process is employed.

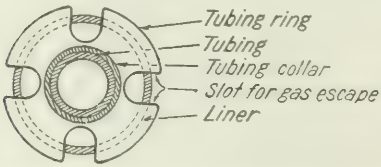


FIGURE 5.—Tubing ring slotted to permit escape of air and gas. (See fig. 4).

On a few properties some of the wells have displayed a tendency to flow; and it is possible that with the proper application of compressed air, the wells can sometimes be made to flow their production.

PROPORTION OF AIR WELLS TO PRODUCING WELLS.

The proportion of air wells to producing wells will depend not only on the local conditions on each property, but also on the principle on which the process is being operated. If back pressures are being used, different factors enter into the problem than if no back pressures are being maintained in the producing wells. Experience without the use of back pressure indicates that the best practice is to distribute many air wells as uniformly as possible among the producing wells. More recent experience with the use of regulated back pressures in the manner discussed elsewhere indicates that fewer air wells are necessary, and that the wells so used can be chosen by their capacity for taking air rather than because of their central location among a group of producing wells. The operator will decide from the system he is using and from the local conditions which practice to follow.

Where back pressures have not been used the tendency has been to increase the proportion of air wells, the average among 34 properties shown in Table 4 being 1 air well to each 2.6 producing wells. At first consideration the operator is apt to think that as few air wells should be used as possible, thus saving more of the wells for pumping, but experience has shown otherwise.

Figure 6 represents a square tract of 160 acres for which ideal conditions are assumed: that is, the wells are spaced evenly and the character of the oil sand and other conditions are uniform over the property. There are 25 wells, of which 4 are air wells and 21 are pumped, there being 1 air well to each 5¼ pumping wells. The air from each air well passes through the sand to the surrounding pumping wells and presumably affects all the sand between these wells. It is likely, however, that it affects less the strip of oil sand between the line wells and the property line. The diagram illustrates the principle that if there are not enough air wells the oil will not be moved directly between the air wells and the pumping wells, and parts of the oil sand will remain practically unaffected.

The air enters the oil sand at the air well, spreads out, and is distributed among the several adjacent pumping wells. Each pumping well gets but a fraction of the air forced into the air well, and consequently the rate of movement of the air through the sand is much less near the pumping wells than near the air well. If there are four pumping wells to each air well, the effect is like filling a 2-inch pipe through a 1-inch opening. To get a sufficient quantity of air into the sand, it is necessary to use high pressure in the air wells, and this requires more power and occasions greater frictional losses both in the surface equipment and underground. Where the air wells are scattered far apart, the air must travel long distances through the sand, which also increases frictional losses. With a greater number of air wells, the same quantity of air can be forced into the sand with less pressure, and consequently with a saving in power and frictional losses. Moreover, the compressed air is distributed more uniformly over the property, so that all parts of the sand will be affected. The equipment cost for an air well is much less than for a pumping well; likewise operating expenses and troubles are lessened, and, if the same production can be obtained by changing pumping wells to air wells, a considerable saving may be made.

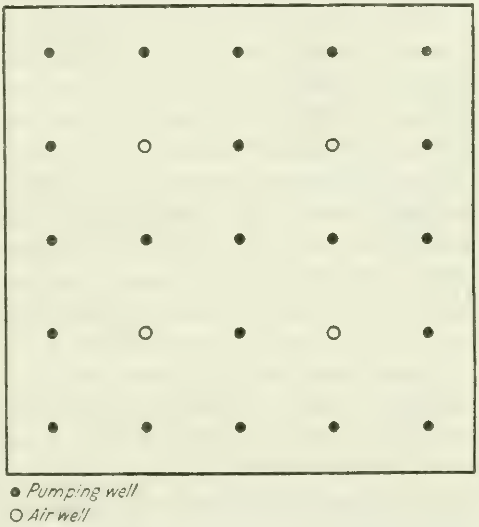


FIGURE 6.—Diagram showing distribution and spacing of air and pumping wells under ideal conditions on a square 160-acre tract.

As a matter of fact, the conditions in the sand are far from being uniform, as is assumed in figure 6, and some parts of the sand will offer much less resistance to the movements of the air than other parts. The problem is to get the air into all parts of the sand where there is oil and to prevent it wasting through parts where there is little or no oil. The air will take the easiest and the shortest routes between the air wells and the pumping wells, and hence there is a marked tendency for the air to pass around and not affect the tighter parts of the sand or the parts not in the path of the air. Where back pressures are not maintained in the pumping wells, uniform distribution of the air underground is sought by having many air wells uniformly distributed over the property in the manner described.

By maintaining back pressures in the pumping wells, the pressure underground may be built up and eventually the air will find its way into every part of the sand on the property no matter where it originally enters. On this principle, the logical way is to get the air into the sand in the easiest way possible and through the fewest number of wells. The wells where the sand takes the air with least resistance are selected and no more than are necessary to take all the air at the desired pressure, back pressure being maintained in the pumping wells. It is thought that the air will then find its way into the tighter parts of the sand with less resistance, for the air will be distributed through the open parts, and will come into contact with the tighter parts over much larger areas than where the air finds its way into the sand through the walls of "tight sand" wells.

Maintaining back pressures on the producing wells is a recent development, and experience has hardly given a settled policy in regard to the best manner of distributing and proportioning air wells. Some of the factors entering into the problem have been discussed, but in all cases trial and experience will have to determine the best practice on each property whether regulated back pressure is being used or not.

SELECTION OF AIR WELLS.

Perhaps a more important feature in the selection of an air well than its situation is the condition of the oil sand.

The tendency is to use "open-sand" wells for taking air, and "tight-sand" wells for pumping, because the former usually waste too much air when pumped, and the "tight-sand" wells require too great pressure in taking the air and cause large frictional losses. When a pumping well begins to by-pass or waste much air, it had better be changed into an air well. Frequently it becomes necessary to change a well for this reason, and the entire system of air and pumping wells may be rearranged during the life of a property. Figure 7 shows the location of the wells on a property near Pennsville, Ohio, and how the air wells had to be arranged in actual practice. Some of the air wells were "by-pass wells," and wasted so much air that they could not be pumped economically. They are arranged in lines apparently in accordance with local variations in the character of the oil sand. On account of the irregularities in the sand, pumping wells on one side of an air well may be practically unaffected, while those on the opposite side may show the effects to a considerable distance.

A few operators advise that all wells on a property be tested at the time tests are made for determining the size of the compressor in order to get an index of the conditions in the sand at each well. Considerable variation will be found from well to well, and these data will lead to a more intelligent determination of what wells to pump, which pumping wells will need regulated back pressure, and which wells will receive air readily. This information is likely to prove of much value during the life of the property.

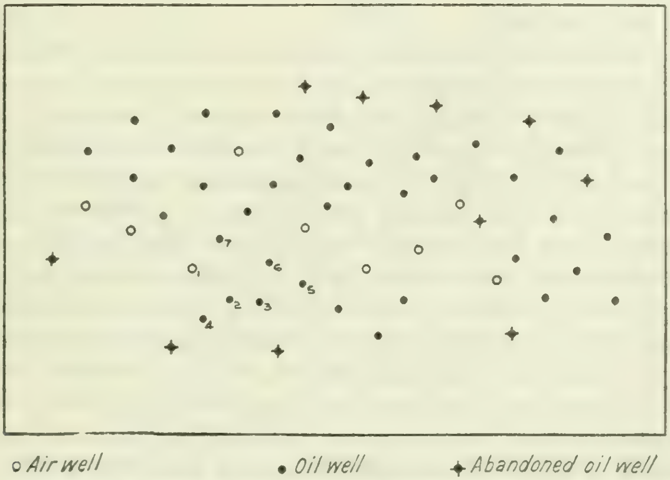


FIGURE 7.—Plat of oil property on "Chesterhill streak" near Pennsville, Ohio, showing irregular distribution of air wells caused by irregularities in the oil sand. Making well No. 1 an air well greatly increased the yields from wells 2 and 3 for a time; then the air "blew through" and made "by-pass" channels. No. 4 was a tight well and was not affected. Nos. 2 and 3 were then shut in and this increased the yields from Nos. 5 and 6. No. 7 and the other wells above were also benefited.

The condition of the well itself has much to do with the choice of an air well. The well must be in good shape to take air readily, and with no chance of its wasting into other formations. The relative productiveness is also considered, as the producer naturally dislikes to sacrifice a good pumper. However, the relative productiveness often changes after the process has been in use, and even old, abandoned wells have been rejuvenated and made producers.

Air wells are placed at a distance from property lines as much as possible, unless an agreement can be reached with the neighbor, because the air will not stop at property lines and may be lost to the operator. Furthermore, the air crossing the property line will move oil with it, at the expense of the user of the process. These considerations are more important where the neighbor is not using the process or his wells are being gas pumped. When only one property uses the process in a field of considerable size, there may be difficulty in building up the pressure, because the air will spread to other properties. This can be largely controlled by placing the air wells centrally on the property and gas pumping the line wells. Where a neighbor is also using the air process it is advisable to reach an agreement with him, if possible, to arrange to force air into the strip between the line wells, which otherwise will be affected only indirectly.

The question has frequently been asked the writer where the air wells should be located with reference to the geological structure of the sand. It is a question not always readily answered, but the following points in regard to it may be considered: When the air forces the oil up a slope it is moved against gravity, whereas if forced down the slope gravity aids in the movement, but in fields like those east of the Rocky Mountains, the slopes of the beds are so slight that this fact seldom need be given consideration among the many more important factors influencing the choice of air wells. At times, however, the oil sand is continuous with an exhausted gas sand. If air is forced into the oil sand, it will tend to move toward the exhausted gas sand carrying with it oil, which will be disseminated in the barren strata with slight chance of recovery. Under such conditions it is better to force air into wells in the former gas sand, build up the pressure, and force oil away rather than toward the gas sand. When the area of the exhausted gas sand is not too great this may be readily accomplished, but there are some pools which are continuous with an exhausted gas sand whose capacity is so great that it may be impracticable to fill it even at low pressures. Properties too close to such areas of exhausted gas sands might have trouble in using the process, owing to the escape of air, but the movement of oil and gas in the sand is so hindered by frictional resistance that the process may perhaps be satisfactorily used fairly close to the exhausted gas sands.

At times it has been found advisable to drill new wells on a property where the old wells have not been advantageously located. The new wells may be pumped or used as air wells for which they are favorably adapted, as the sand about the hole will be free from paraffin or waxy sediments.

UNDERGROUND WASTE OF AIR.

Experience has shown that in the use of the process it is necessary to exclude the air from formations other than the oil sand. Numerous instances have demonstrated that if this is not done, much air may waste into unproductive strata and the efficiency of the process be reduced accordingly. For this reason it has become the general practice to pack the air wells directly above the oil sand. Experience in the gas-producing business has led to a similar practice in finishing gas wells.[a]

On both the Dale and the Buck Run properties, which are parts of the historic Joy farm, Morgan County, Ohio, the writer witnessed air coming to the surface in numerous places. Many wells drilled in the early history of the pool had been abandoned and their locations lost, but when the air was forced into the sand they allowed the air to reach the surface as well as to waste into other formations. During the first year the process was used these wells had to be found and plugged. Through these old holes the air got access to formations overlying the oil sand, spread through them, and reached the surface at low places along the creek bottoms. On the Buck Run the air bubbled continuously from joint cracks in the shale along the creek bottom. After the old wells had been searched out and plugged, this escape of air diminished. At the time of the writer's visit to the Poplar Ridge property, near Malta, Ohio, air was still issuing from joint cracks and coal seams, and through laminations in the shale. The writer witnessed an instructive example of the permeability of shales and coal on this property. From a well drilled on a bank some 75 feet above and 150 feet distant from the creek bottom, the muddy water used in drilling passed through a thin streak of coal and also through a platy micaceous shale and showed in the face of the creek bank.

Other instances of air escaping, not witnessed by the writer, have been reported. In one, the air came to the surface in numerous places although there were no old abandoned wells and the oil sand was between 300 and 400 feet deep. The air did not appear at the surface until the process had been in use for over a year. In another case the air passed through the formations above the oil sand and blew out around the casing of a well a thousand feet distant. The oil sand is about 600 feet deep on the property and no sand is reported above it. On a property in Pennsylvania partial failure of the process is attributed by the user to waste of air into old, abandoned wells and into the overlying formations where the air wells had been packed too high.

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[a] McMurray, W. F., and Lewis, J. O., Underground wastes in oil and gas fields and methods of prevention: Tech. Paper 130, Bureau of Mines, 1916, 28 pp.

The permeability of shales has generally been underestimated. They often contain thin seams of sand or porous material, which, in the aggregate, may have a large capacity. Even shales that contain no sandy layers may be permeable along the bedding planes and joint cracks, especially the hard, slaty varieties. There are thousands of gas wells in northern Ohio, Pennsylvania, and New York, particularly along the shores of Lake Erie, whose production is derived from accumulations of gas in beds of this character.

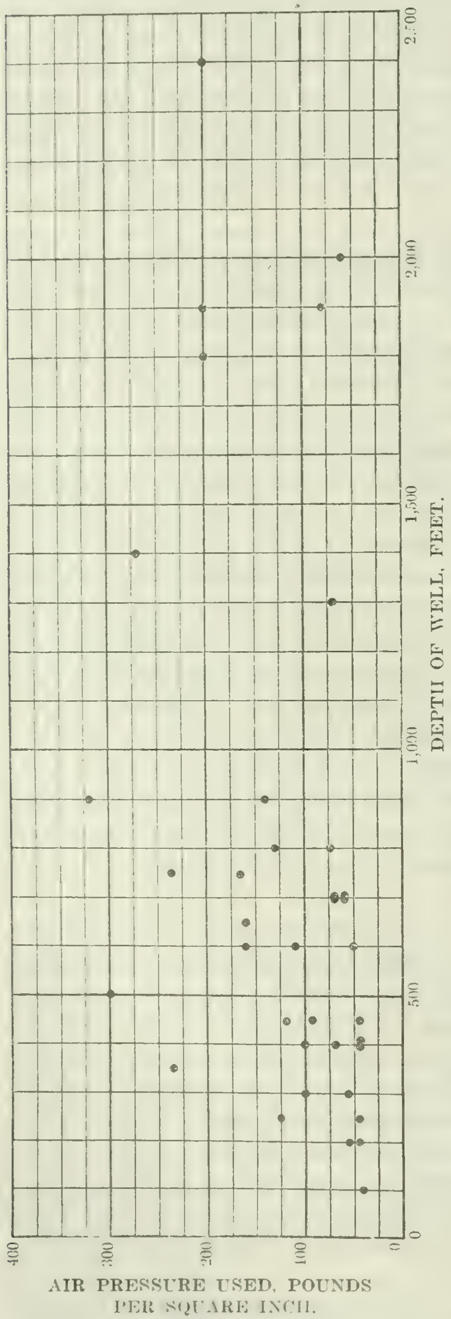

FIGURE 8.—Chart showing relation between air pressures and well depths. Dots represent different properties.

In the cases cited, the migration of the air was made known at the surface, but large wastes may readily take place without surface evidence. Unless there is definite proof that the overlying formations are not permeable, it is advisable not to expose compressed air to them.

AIR PRESSURES USED.

On 41 properties using the process, which include 1,600 wells, the highest pressure used is 320 pounds; the lowest, 40 pounds; and the average is 115 pounds. As high as 600 pounds has been used temporarily.

The pressures used at the present time have not been worked out from a full and systematic study of all the factors involved, and it is not to be assumed that they are in fact the best pressures that might be used. This is a problem needing more extended investigation. In the limited experimental investigations conducted by the writer, it was found that by higher pressures the oil could be expelled from the sand more quickly even when using smaller volumes of free air, but that the ultimate extraction was approximately the same as with lower pressures. Pressure thus appears to be primarily a factor of time and the best pressure to be used can be gaged from the relation between the increased daily production and the increased operating costs or difficulties. In field practice each case will show a complexity of elements often conflicting that must be considered, such as by-passing, effect on the quality of the gas, wastes of air, use of regulated back pressures, etc., so that a study of the special conditions on each property will be necessary, as well as an understanding of the general principles involved.

The pressures used have little relation to the depths of the wells, but are intimately related to the character of the oil sands, as is shown in figures 8 and 9 and Table 4. Coarse porous sands like the First Cow Run take the lowest pressures, whereas fine, tight, or slaty sands require pressures much higher. A large number of the properties operating the Smith-Dunn or Marietta process are producing from the First Cow Run sand in the shallow pools of southeastern Ohio and adjacent parts of West Virginia, where the deep sands are generally of a tighter nature. Where the

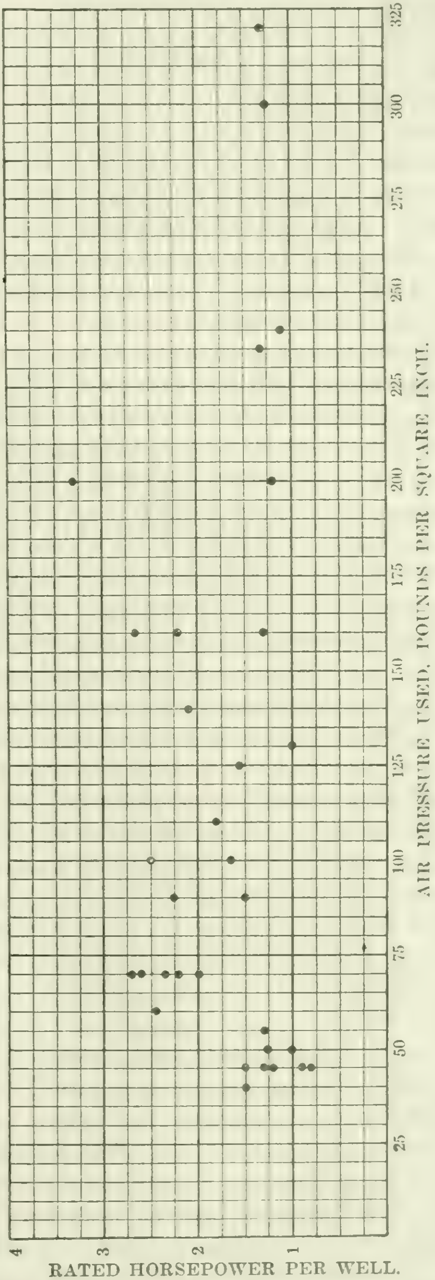

FIGURE 9.—Chart showing relation between air pressures and rated horsepower per well. Dots represent different properties.

deep sands are coarse and porous, low pressures can be used, and where the shallow sands are tight, high pressures are required. For example, wells in the Keener sand in Tyler County, W. Va. (property No. 40, Table 4), are reported to use a pressure of only 50 pounds, although 1,700 to 2,500 feet deep, whereas wells in the Peeker sand (property No. 11, Table 4), in Ohio, require a pressure of 240 pounds at a depth of 300 to 400 feet. Originally the deeper sands had the higher rock pressures, but during the lives of the wells the gas was dissipated until the pressure was no greater than in shallow sands by the time the Marietta process was started. As the deeper sands originally contained the higher pressures, less oil may have been left in the sand, and it is possible this may influence the necessary pressures somewhat.

The pressure necessary will also depend upon the quantity of air being forced into the sand, for if it is attempted to increase the quantity of air, the pressure must be increased correspondingly. For this reason increasing the number of air wells often allows a reduction in necessary pressure. This is illustrated by a property producing from the Peeker sand. There were 93 wells on the property (No. 11, Table 4), 32 of which were air wells, and the pressure used was 270 pounds, but when 5 air wells were started on an adjoining property only 240 pounds was required.

The character and distribution of the contents of the sand likewise affect the resistance to movement, and hence affect the required pressure. An exhausted oil sand, or one containing gas at low pressure, will offer much less resistance than one saturated with oil or water, provided the texture of the sand is the same. A fully saturated sand requires more pressure than one largely drained as shown experimentally, and one containing water requires less pressure than oil, as the frictional resistance is less. However, it may be necessary to use large volumes of air to get results where there is less oil, and hence higher pressures. The required pressure varies from well to well, and from property to property, in accordance with conditions at each locality. Often two adjacent wells producing from the same sand will show wide variations. For example, it is reported that of two adjacent wells, one took the full capacity of a testing plant at 40 pounds, whereas the other required 150 pounds.

The pressures used are not constant and will vary throughout the life of the property. It is often found advisable to change the pressures, as underground conditions change because of the removal of oil. It is likely that greater pressures will be required as the process continues to be used, especially as back pressures may be used on the pumping wells, and hence correspondingly higher pressures must be used at the air wells. The movement of the air through the sand is caused by differential pressure, and whenever back pressures are maintained at the producing wells, the pressure at the air well should be increased also. If there is still natural pressure from gas in the sand, higher pressures will be required. For example, if the natural pressure is still 50 pounds, a pressure greater than 50 pounds must be used at the air well to get results.

There is always a minimum pressure below which the oil sand will take but little air, or not enough to appreciably increase production. There is also a maximum pressure which can not be exceeded without enlarging or increasing the efficiency of the compressor plant or the conditions of operation. This maximum pressure shows that a balance has been reached between the volume of air being forced into the sand at that pressure, the volume of air issuing from the pumping wells or being wasted underground, and the frictional resistance in the oil sand. By enlarging the capacity of the plant or by reducing waste of air and gas at the pumping wells and underground or by maintaining back pressures in the pumping wells, the maximum pressure may be increased.

In practice the preliminary tests indicate approximately what pressures will be required to force certain volumes of air into the sand. After the process has been put into actual operation it is determined experimentally what pressures and volumes are most efficient. In general, more oil can be recovered by increasing the volume and pressure, although some operators report that this is likely to cause by-passing and waste of air. The best practice seems to be to build up the pressure, gradually noting the effects on production, and in this way determine the maximum efficiency from both the increase of production and the costs of operation.

Very often the pressure can be reduced after beginning the process, it having been found that in many instances the sand will take the air more readily after movement through the sand has started. One producer in West Virginia reports that a pressure of 600 pounds was necessary at the start, but later 200 pounds was sufficient. This is an extreme instance, for usually any reduction of pressure reported is comparatively much less. In the later life of the properties it may be necessary to increase pressures once more.

There is always a loss in pressure between the compressor and the air well which should not be more than a few pounds if the fittings are tight, the pipe not too small, or the air lines too long. In the oil sand there is a considerable loss in pressure between the air wells and pumping wells, but if the latter are closed in, the pressure in time will build up. There are few records of closed-in pressures in pumping wells. On a property where the pressure used was 300 pounds a pumping well showed a closed-in pressure of 80 pounds within an hour. When the process is stopped, the pressure quickly reduces at first and then more and more slowly.

On a property at Bradford, Pa., where a pressure of 80 pounds had been in use, and the production had been increased about seven times, production returned to normal in three months' time after the input of air was stopped. On a property using a pressure of 240 pounds the pressure dropped to 145 pounds in four days after stopping the air. The curve in figure 10 is plotted from a gage record on an air well (on property No. 6, Table 4) and shows how the pressure in the air well dropped after the pumping of air was stopped, the closed-in pressure of the oil wells on the property being about 30 pounds.

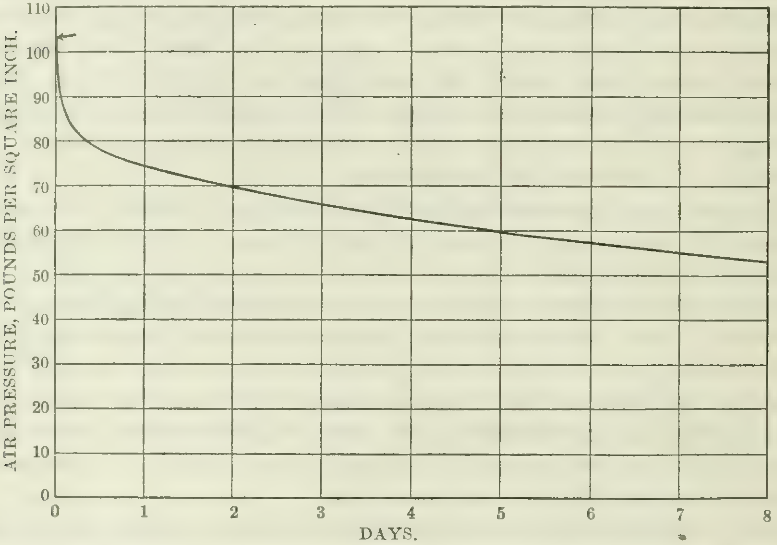

FIGURE 10.—Curve showing the declines of pressure in an air well after stopping the input of air. Plotted from recording gage chart on property No. 6, Table 4. The decline represents the equalization of pressure in the air well and the closed-in pressure of the oil wells, which was about 30 pounds.

To overcome the different rates at which different parts of the oil sand in a property take air because of the variations in the nature of the sand, two methods are possible. One is to regulate the pressure at the intake—that is, at the air wells—the other, at the producing wells where the air escapes. The latter method, which is thought to contain the best principles, is described elsewhere. The pressures at air wells taking air too readily can be regulated by reducing valves in the air lines or by having two systems of air lines carrying different pressures. This can be done when there are two compressors on the property working at different pressures or by having the two cylinders of a two-stage compressor deliver air at different pressures. The purpose of regulating the pressures at the air well is to more nearly equalize the volume and energy delivered to the sand at different parts of the property, otherwise one part of the property may receive little air and be practically unaffected. In regulating the pressures at the air wells some mechanical difficulties are encountered, and this method is not considered to be as efficient as regulating the pressures at the producing wells and is seldom used.

VOLUMES OF AIR USED.

On an average about 10,000 cubic feet of free air is used per well daily; that is, 30,000 cubic feet of air is forced into an air well daily on a property where the proportion is one air well to two pumping wells and 40,000 cubic feet daily where the proportion is one air well to three pumping wells. The minimum is about 5,000 cubic feet of air per well daily and the maximum about 20,000 cubic feet. Where the pressures are low, larger volumes are used, and where the pressures are high the volumes are small. In thick, open-textured sands, or sands subject to by-passing, the volumes will be large; whereas in tight sand high pressures and small volumes will be used. The operator may largely control the volume of air by changing the horsepower used per well.

As brought out experimentally, larger and larger volumes of air will be required to expel each additional barrel of oil from the sand, consequently with the continued extraction of the oil, the cubic feet of free air necessary on the property will be increased. As with the pressures, it is by no means certain that the present practice in regard to volumes of air used are the best possible, and hence further investigations may show that the figures cited do not represent the greatest possible efficiency even for the districts where used; furthermore, it is probable that outside of the Appalachian field greater volumes will be required, which may be gaged roughly by the comparative quantity of oil that has been produced per acre of oil land.

POWER REQUIRED.

The energy used in practice appears to be much the same for the different pressures and volumes used, and consequently for the different kinds of oil sands, as is shown by figure 9 on page 53. According to the limited data on which this figure is based, there is some evidence that the moderate pressures may require more horsepower per well, and hence more energy than for the higher pressures and tighter sands. But the data are too few at this time to establish general conclusions, and possibly future experience may alter the practice.

If the conclusions indicated by figure 9 can be accepted they show that the energy or horsepower required per well will not depend on the character of the sand so much as upon other factors. In tight sands the pressures are increased, but the volumes are decreased correspondingly, as is indicated in the figure, so that a smaller volume of air suffices. The resistance is undoubtedly greater in the tight sand, but this may be largely compensated by greater efficiency of expulsion, for in the open sands the energy is more likely to be wasted by the air slipping through parts of the sand without doing work. This indicates that the energy or horsepower required per well depends more on the thickness and degree of saturation of the sand, the wastage of air, and what has been termed the "efficiency of expulsion," or proportion of energy actually expended in moving oil. For the same kind of sand and for conditions otherwise similar an oil sand 20 feet thick would require twice the volume of air to maintain the same pressure as a sand 10 feet thick, and consequently twice the horsepower per well. The wastage of air and pressure in the plant or the waste of air underground through improperly finished wells or by escape to other properties will likewise necessitate the use of more power, as will by-passing and other forms of inefficiency within the oil sand which reduce the proportion of the energy actually expended in moving the oil.

The results shown in figure 9 are based upon the rated horsepower of plants in actual use. In all probability many of the plants are unnecessarily large, whereas others are inadequate in size. Furthermore, the actual delivery is seldom the same as the rated horsepower, and in practice many plants fall far below the rated power, owing to inefficiency in both the compressor and the gas engine.

HOW THE AIR MOVES THE OIL.

The three physical principles upon which the compressed air moves the oil through the sand are, first, by direct pressure; second, by the air going into solution under pressure near the air wells and later expanding near the pumping wells; third, by the carrying of vapors.

Many producers believe that the air displaces the oil and pushes it ahead in a solid body in the same way that a body of oil appears to be collected and driven ahead of a "water drive" in the Bradford field. At Bradford a well in the path of an approaching flood gives no indication of the proximity of the flood until it nearly reaches the well, although it may be very close, as shown by figures 27 and 28, printed on page 98. The production of oil suddenly increases and is maintained for a variable period, after which the volume of water increases quickly and ends the life of the well. In the Smith-Dunn process the air reaches the well first and is followed by an increase of production, which takes a few months to several years to reach a maximum, and during the time the process is used air is passing through the sand continuously. In the groups of wells in the Bradford field (see fig. 32, p. 115) around an air well, wells 7 and 8, respectively 1,500 and 2,150 feet from the air well, were affected to the extent of having 26 and 10 per cent of air in the gas, yet the oil production remained unaffected though the production of closer wells was increased ninefold. These facts show that there is no "air drive" comparable to a "water drive" and in the sense meant by the producers mentioned and that the air does not work solely on the displacement principle.

The writer's theory is that the oil is probably worked into a froth by the air, and bubbles are continually forming and breaking in the pores of the sand, all the time moving with the air toward the pumping wells. This condition is indicated by experiments.

ENERGY UTILIZED IN MOVING OIL.

In passing through the oil sand the full energy of the compressed air is not expended in actually moving oil. Some of the energy is used in overcoming the frictional resistance in the sand, and much of it is wasted, the air slipping through the sand without moving oil. This waste of energy is comparable to slippage in an "air-lift" for pumping oil or water. It is "by-passing" on a small scale and will be greatest in a coarse open sand or with a light oil of low viscosity and increases enormously with the progressive extraction of the oil from the sand; consequently, although the frictional resistance will be higher in a fine, tight sand, or with heavy, viscous oil, the waste of energy will be less and the actual proportion expended in moving the oil may be but little more. This is suggested by figure 9, which indicates, so far as the limited data permit conclusions, that no more energy has been required for tight sands using high pressures than for open sands using low pressures, and is also indicated in experiments.

The proportion of energy actually expended in moving oil may, as was previously stated, be conveniently referred to as the "efficiency of expulsion." When the sand is full of oil, the efficiency will be high; but it will become less and less as the sand is depleted, because the slippage will increase. It may be expected that the efficiency of expulsion will decrease with time as the oil is removed, in accordance with experimental results. This loss of efficiency can be combatted by increasing the volume of the air passing through the sand, or possibly by alternately building up and releasing the pressure. By increasing the volume, the air is forced into new passages through the pores of the sand not affected previously. By building up the pressures it is expected that the oil in the tighter parts of the sand will absorb and become charged with compressed air: and when the pressure is released the air will expand and force this oil in the direction of the pumping well or toward the air passages and lines of least resistance in the formation, where the pressure will be reduced most rapidly. An intermittent building up and releasing of pressures would tend to cause the oil to move toward the air passages and diminish "by-passing" and loss of efficiency. It is probable that the decline in production shown by some of the properties using the air process (see production curves on pp. 68 to 74) represents loss in efficiency of expulsion more than depletion of the oil.

TENDENCY TO FOLLOW CHANNELS OF LEAST RESISTANCE.

The passage of the air through the oil sands, as previously stated, is along the shortest lines of least resistance between the air wells and the pumping wells. If the sand were uniform in character the air would travel directly from an air well to each of the adjacent pumping wells through a comparatively narrow passage, leaving a large part of the sand body practically unaffected, but the variations in the character of the sand cause the air to travel through irregular and devious channels. In numerous instances, pumping wells on one side of an air well have remained practically unaffected, while the air traveled through roundabout channels and reached wells in most unexpected places. By-passing is also a common phenomenon, the air following a former gas-bearing stratum, or the nearest exhausted, coarsest and most porous layer in the oil sand. The by-passing channels may take all the air that the plant can deliver so that very little enters the other parts of the sand. This tendency to follow channels, that are likely to constitute but a minor part of the sand body, will be the most serious problem to overcome in the later life of all properties. Even if by-passing does not cause trouble when the process is first started, eventually the oil will be expelled from the channels of least resistance, and by-passing established. This has occurred many times in practice, and wells which gave good response at first have "blown through," the production decreasing at the same time. If reliance had to be placed solely upon the driving power and the direct pressure of the air, the only recourse for the producer in such a case would be to increase the volume and the pressure of the air going into the sand so as to force the air to enlarge the channels and thus affect a larger part of the sand body. This would become more and more difficult to accomplish, and sooner or later the practical limits would be reached, although a vast quantity of oil might remain in the rest of the sand.

PRINCIPLE OF SOLUBILITY OF GASES IN OIL.

Because of the solubility of gases under pressure and their later expansion upon release of pressure, it becomes possible to affect the oil in all parts of the sand. The air is absorbed by the oil at the points of high pressure near the air wells, and moves through the oil toward points of low pressure in the same way that the gas, originally dissolved in the oil, flowed toward the wells when they penetrated the oil sand. It thus becomes possible to recharge the sand so that the oil, regardless of its location, is stored with energy once more. This offers a solution for the problems arising from the variations in the sand body and the tendency of the air to follow the channels of least resistance.

OIL IN TIGHTER PARTS OF SAND.

It is often contended that the tighter parts of the sand contain only a negligible quantity of the oil and that practically all the production is derived from the thin pay streaks. The author does not hold to this view, for although the greatest production may have come from the pay streaks, especially during the early life of the well, the amount of oil held in the other parts of the sand, when the property has become so depleted that the air process is necessary, may be relatively many times more. Just as a tight-sand well comes in at a lower production, but holds up better than an open-sand well, so in the later life of a well with a thin pay streak it may be the tighter parts of the sand that yield most of the production. It is often reported that in shooting old wells greater response is gotten from the tighter parts of the sand. The rich pay streak is apt to represent but a small part of the total thickness of the sand, often but 2 or 3 feet in a bed ten or more times thicker, so that although the porosity of the pay streak may be greater than the rest of the sand the total oil content may be much less.

ALTERNATE CHARGING AND DISCHARGING OF WELLS.

A test which has been made repeatedly is to force air or gas into a well for a time and then to release the pressure. The air or gas usually comes back with much vigor: at first it may be entirely free from oil, later it will show oil vapors, and at last, in most wells so treated, oil is brought back in considerable quantities. Sometimes oil appears within a short time after the pressure is released, at other times it may take several days, and occasionally a long time for the oil to come back. The writer witnessed one instance in which a well, into which air had been forced for over a year, within an hour after the pressure had been released was spraying oil. In some instances wells have flowed oil with the return of the air on release of the pressure. This seems to be direct proof that the air is not acting solely as a driving force, but has gone into solution in the oil and upon the release of pressure at the air well expands and expels the oil just the same as when the well was first drilled into the sand and the oil was charged with natural gas. On one property near Marietta, Ohio, so small that elaborate equipment is not warranted, production is successfully obtained by alternately charging and discharging the wells.

USE OF BACK PRESSURES.

The use of regulated back pressures is based upon the principle of charging the oil with air under pressure as well as overcoming the differential movements of oil through the tight and open parts of the sand. It is the writer's belief that this principle will have to be resorted to more and more in the later life of the property in order to obtain the oil from parts off of the channels of migration or pocketed in the sand. By alternately charging the oil with compressed air and releasing the pressure the field would go through a series of producing stages, as has been accomplished experimentally. If the field were shut in and the pressure built up until all the pores of the sand were filled with air at high pressure, and all the oil was charged with air, it is to be expected that when the pressure was released the conduct of the field would be similar to what it was when first opened up. The productions, of course, would be relatively smaller and the exhaustion relatively faster, but after the air had been expelled the sand could be charged again with air and the process repeated.

To date the only special applications made of the principle of the solubility of air under pressure in oil have been by building up the pressure in one well and later releasing it, or by carrying regulated back pressures on a few troublesome wells. The stage has not been reached on any property where it has become necessary to charge and discharge all the wells on the property in the manner considered. The practical operation of the process has not been sufficiently developed, but it is believed that in the future the producers will have to rely on this principle more and more, and practical methods of applying it will have to be worked out. It may be practical on a large property to alternately charge one group of wells while the other wells are producing, or by maintaining back pressures on all the pumping wells and using a correspondingly higher pressure on the air wells so as to get the same differential pressure between air and pumping wells it may be practical to charge a sand while production is maintained, and at intervals the pressure can be released. For example, in a property using an air pressure of 100 pounds back pressures on the pumping wells could be raised gradually to 100 pounds, while the pressure at the air wells was increased to 200 pounds, and this pressure maintained until the operator was satisfied that all of the oil sand was charged. By discontinuing the back pressures the air in the sand at pressures of 100 to 200 pounds would be released and would start the oil moving from all parts of the sand toward the pumping wells. To apply such a method, however, on a small property might not be practical except with the cooperation of neighboring producers.

CHARACTER OF THE GAS FROM THE WELLS.

The analyses of the air-gas from oil wells where the process is used, given on page 80, show that it contains appreciable quantities of gasoline vapors. Theoretically it might be possible to vaporize and remove the lighter fraction, even from the oil wetting the sand grains, by passing air through continuously, which has been accomplished experimentally. It is interesting to note this was attempted in 1894 in parts of the Trenton limestone pools of Indiana and northwestern Ohio.[a] The principle is of practical importance, since it causes the enrichment of the air-gas which must be used for raising power. On some properties there is an excess of air-gas rich enough for extracting gasoline, and by the absorption process for extracting gasoline from natural gas this may become a profitable source of revenue in the future.

"BY-PASSING" AND "BLOWING THROUGH."

"By-passing" and "blowing through" of air are two of the greatest difficulties to be overcome in the successful use of the Smith-Dunn or Marietta process. By-passing is where the air takes the line of least resistance, usually along the top of the oil sand through a former gas stratum or a drained part of the sand. Blowing through is where the air removes most of the oil from the most porous part of the oil sand and establishes by-passing.

Blowing through does not make itself evident when the process is first started. A well will be producing much oil and very likely be one of the best wells on the property, when a considerable increase in the quantity of air wasted will come about, showing that the most porous part of the sand, which is generally the former pay streak, has been cleared of oil and is letting the air pass through with little restriction. The yield of oil generally decreases, and the well will become of little value as a producer, while it wastes so much air that it will seriously affect the production of the whole property. It may take several months or even several years before a well will blow through. It may be expected that in course of time most of the wells will be subject to this trouble to some extent, and if there were no way of overcoming this difficulty the compressor plants would have to be enlarged continuously, as first the most porous layers and then the next most porous layers were blown through in succession until it became impracticable to enlarge the capacity of the plant further. It is thought that blowing through is one of the causes of the decline in production of some of the properties using the air process longest, and Messrs. Smith and Dunn report that they have favorably influenced production on properties so affected by taking means for overcoming this difficulty.

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[a] Jordan, E. T. J., Report of State supervisor on natural gas: 19th Annual Report, Dept. of Geol. and Nat. Resources of Indiana, 1894, pp. 134–136.

By-passing becomes evident soon after the process has started. The effect is the same as in blowing through. Energy is wasted, for the air passes through the sand without doing work, and so much air may escape at the pumping wells subject to by-passing that it will seriously affect the success of the process. Practically all the air forced into the sand may be diverted through these by-pass channels so that the parts of the oil sand containing the most oil may receive no benefit. Not only is the oil production affected, but the gas becomes lean and may be made unfit for use. Lean gas on any property at the present time is, because of the comparatively recent date of introducing the process, an indication that the air is not coming into contact with oil and is not doing its full quota of work.

The simplest method of overcoming this trouble is to shut the well in or to change it into an air well, and frequently it becomes necessary to make these changes after the process has been started, for it is better to sacrifice a small producer than to permit the escape of too much air, as by so doing the production of the other wells is affected. Another method which limited use indicates will be successful is to use regulated back pressures as outlined elsewhere in this paper. Sometimes it is possible to pack or case off the by-pass part from the rest of the oil sand in a new well that has not been shot.

USE OF REGULATED BACK PRESSURES.

The principles of maintaining back pressures on pumping wells have been discussed previously. This method is used for overcoming the difficulties caused by the irregular character of the oil sand, by which the variations in frictional resistance in different parts of the sand are more nearly equalized by holding pressures on those wells where the resistance in the sand is slight. The excessive escape of air from wells subject to by-passing is prevented, so that the air is distributed more evenly over the property and is made to do more work.

The other principle upon which the use of back pressures is based is the building up of pressure in the whole area drained by the wells until the oil in all parts of the sand is charged with compressed air, so that when the pressure is released the oil will be expelled by the expanding air from the tighter parts of the sand.

The use of regulated back pressures is a more recent development in the Smith-Dunn or Marietta process, and although they have not yet been used extensively, the results are encouraging, so that it seems likely that they will be used extensively in the future. Wells which formerly wasted large volumes of air have been controlled and made good producers. In one instance the escape of gas has been reduced from several hundred thousand cubic feet daily to the average amount, the rest of the wells on the property being correspondingly benefited.

The simplest method of maintaining back pressure in a well is to regulate the escape of air-gas from the casing head. A reducing valve is placed on the air-gas line and is regulated until the excessive escape of air-gas is reduced to the average for the rest of the wells on the property. The back pressure necessary will vary with every change of conditions and must be determined experimentally, though by closing in the well and noting the pressure a good index of the back pressure required will be obtained, which should be nearly the same as the pressure of the well when closed in. Maintaining back pressure by this method in a pumping well is apt to decrease the yield somewhat in the same way that production is usually decreased when back pressures are held on flowing oil wells, but this is more than compensated by the beneficial effect on the other pumping wells, for the air that formerly had passed through the sand without expending much of its energy in moving oil is now forced into other parts of the oil sand and made to do more work.

Another method that has been used to maintain back pressures is shown in figure 4, on page 45, and is called maintaining "fluid back pressure." In this method a liner perforated at the bottom is set into the oil sand and packed off above the top of the sand. The tubing is set inside the liner and rests on a tubing ring at the top of the liner. This tubing ring is perforated or notched so that gas may escape from between the liner and the tubing (fig. 5, p. 46).

The working barrel is set high with a flood nipple below, and when the fluid is pumped down to this point, air is let in and the fluid can not be lowered below this level. The flood nipple is so placed that the weight of the column of fluid held in the liner between the top perforations and the fluid nipple approximately equalizes the pressure of the well when closed in. If the pressure is 25 pounds, the flood nipple should be placed about 60 feet above the top perforations in the liner. In a well finished as shown in figure

4, the air-gas accumulates below the packer and bears down on the fluid in the well, forcing it up into the liner and the tubing. Before the fluid has accumulated to such a height that the pressure head is equal to the air-gas pressure, the air-gas may escape readily, but after its pressure has been counterbalanced by the fluid column, the air-gas is sealed in and little can escape. As more oil accumulates it rises equally in the shot hole and in the liner, so that the same difference in level and consequently the same fluid pressure is maintained against the air-gas pressure, though the fluid pressure at the bottom of the oil sand is increased somewhat. In this manner the oil can accumulate until the shot hole is filled. When the well is pumped, the fluid levels within the liner and in the shot hole are lowered equally until they have reached the flood nipple and almost to the top perforations in the liner, respectively, whereupon the well ceases to pump oil.

Instead of finishing the well with a liner, a string of casing can be landed at the bottom and shut in at the top, the tubing and the flood nipple being placed in the same positions in regard to the fluid column as in figure 4. This method has the advantage that the pressure can be gaged easily and continuously, and the position of the flood nipple be changed readily, but unless another string of casing is landed on the top of the sand the air may escape into other formations, or shale may slough off the walls and fall into the hole. Sometimes the flood nipple is omitted and the working barrel is placed low in the well. When the fluid is pumped below the counterbalancing level there is a sudden inrush of air gas which brings in oil from the sand into the hole. When pumping is stopped the fluid rises again and stops the rush of air. By this method a sudden release of air gas takes place every time the well is pumped down.

As the conditions change in the field, it will be necessary to change the back pressure used, from time to time, as varying conditions necessitate.

USE OF GAS PUMPS IN CONNECTION WITH THE PROCESS.

Gas pumping is not commonly conducted in conjunction with the Marietta air process. Where necessary the line wells are gas pumped to protect the property against drainage, especially if the neighboring wells are being gas pumped or where they are not using the air process and there is a movement of air through the oil sand toward the adjoining properties. Gas pumping may occasionally be desirable at wells where the sand is much tighter than the average on the property. The tighter parts of the sand require greater pressure to force the oil through them, and by using the gas pump on wells where the sand is tight the air will be drawn toward these wells and the movement of the air through the oil sand may be more nearly equalized over the property.

The producer at first is apt to consider the suction pump as being a favorable aid to the air process, and that by applying pressure at one end with the compressed air and suction at the other end with the gas pumps the efficiency can be materially increased. The practical limit of a gas pump is only 12 or 13 pounds below atmospheric pressure, and this additional difference in pressure can be obtained far more readily by applying 12 or 13 pounds more pressure at the air well. The principal function of the gas pump, as has been shown, is to permit more gas to expand from solution in an oil sand where the pressure has been reduced almost to atmospheric. The conditions where air is being used are not the same as where gas pumping has been successful. Gas pumping would accentuate troubles from by-passing unless limited to the "tight-sand" wells and is in opposition to the principles of maintaining back pressure in the pumping wells, a method to which the producers will probably be compelled to turn more and more in future.

TIME NECESSARY TO INCREASE PRODUCTION.

The first effects from forcing air into the oil sand are shown by the gas. The volume is increased considerably, and the oil produced becomes livelier and shows more of a "bead." These results are usually noted soon after the pumping of air into the sand is begun, but the actual increase in yield of oil occasionally may be delayed for several months. Usually the increase of oil is closely preceded by an increase of water, and sometimes a well will produce water even if it never has before. The time required for an increase in oil production is variable, as is shown in the production curves presented in figures 11 to 24 of properties listed in Table 4. In one instance the production was increased 3½ times by the third day, but this is exceptional, and in other instances it has taken many months. The increase may be sudden, as in figures 17, 19, and 21, or it may be built up gradually, as in figures 16, 22, 23, and 24.

The producer should not be discouraged until the process has been given a thorough trial. The texture and thickness of the sand, the size of the field, and whether the oil sand is overlain by former gas sand, the capacity of the compressor plant and whether it is run continuously or not, the distance between wells and the relative depletion of the oil sand, all influence the time necessary for the wells to respond to the air. Comparatively, tight sands respond more slowly than open sands, but if the sand has a large capacity it may take some time to fill it up and build up a pressure sufficient to influence production. This is especially true where the top of the sand was formerly gas bearing, or where the air escapes through the sand to other properties. If the wells are far apart, it will take longer for the air to influence production, and if the compressor plant is not large enough, much time may be needed for it to build up pressure in the sand. It is not necessary that the full quantity of gas extracted from the sand be replaced by air at the same pressure, for ordinarily it is possible to employ the air process at a lower pressure than was originally found in the field. There may be places, however, where the capacity of the former gas-bearing sand connected with the oil sand is so large that it is impracticable to use the process.

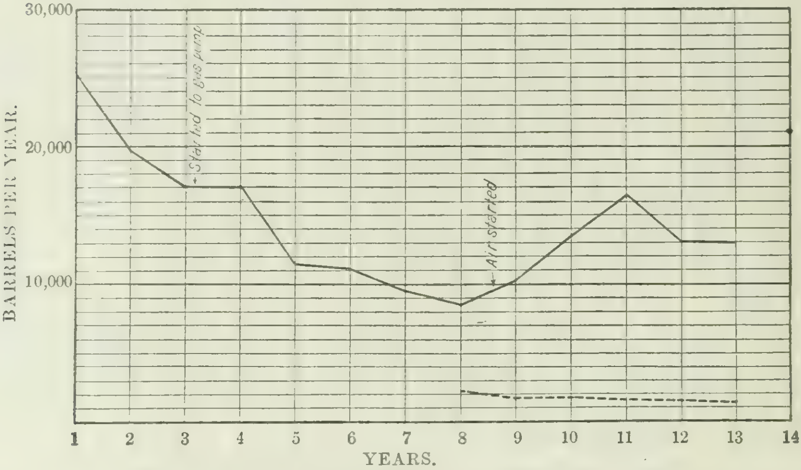

FIGURE 11.—Production curve of property No. 1, Table 4. This is the first property on which Smith and Dunn used compressed air. The lower broken line is the production curve of a part of the property on which air was not being used. Note the effects of gas pumping.

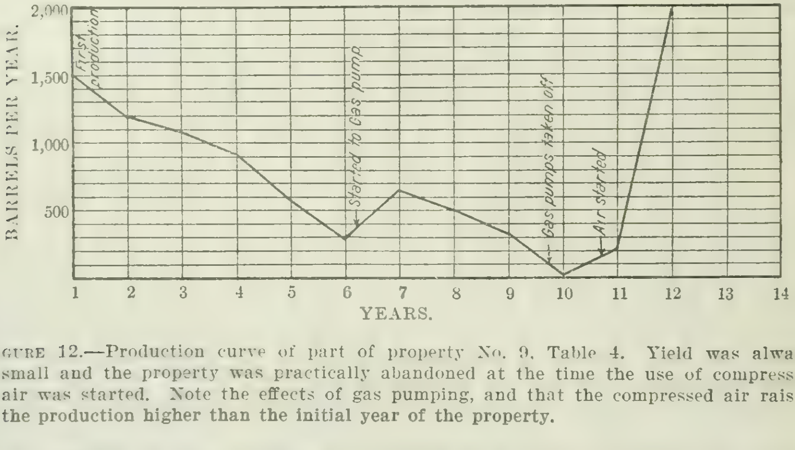

FIGURE 12.—Production curve of part of property No. 9, Table 4. Yield was always small and the property was practically abandoned at the time the use of compressed air was started. Note the effects of gas pumping, and that the compressed air raised the production higher than the initial year of the property.

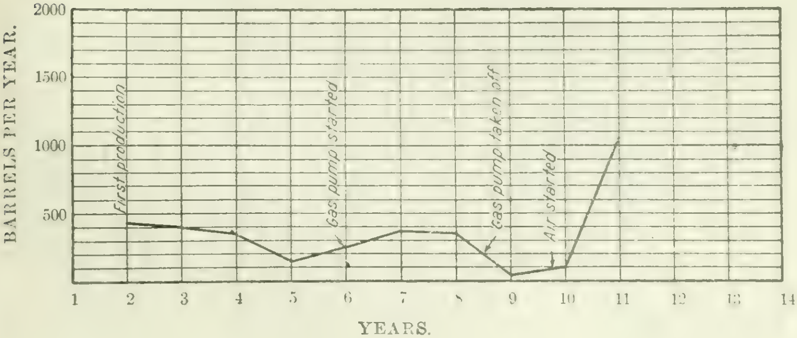

FIGURE 13.—Production curve of part of property No. 9, Table 4 (see fig. 12). The use of compressed air more than doubled the production from what it had been for the first year the property produced. Note the effects of gas pumping.

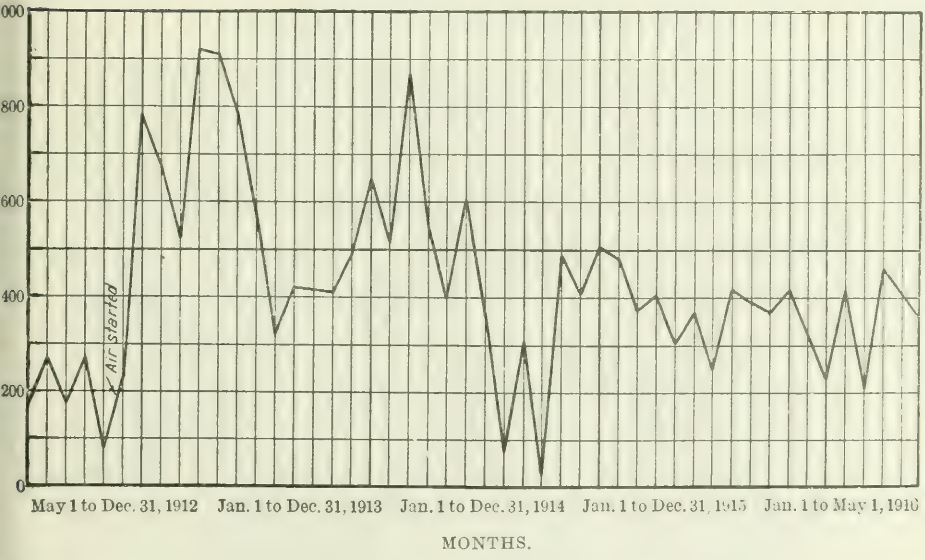

FIGURE 14.—Production curve of property No. 2, Table 4. Note the quick response to the use of compressed air and the declining production after the sixth month.

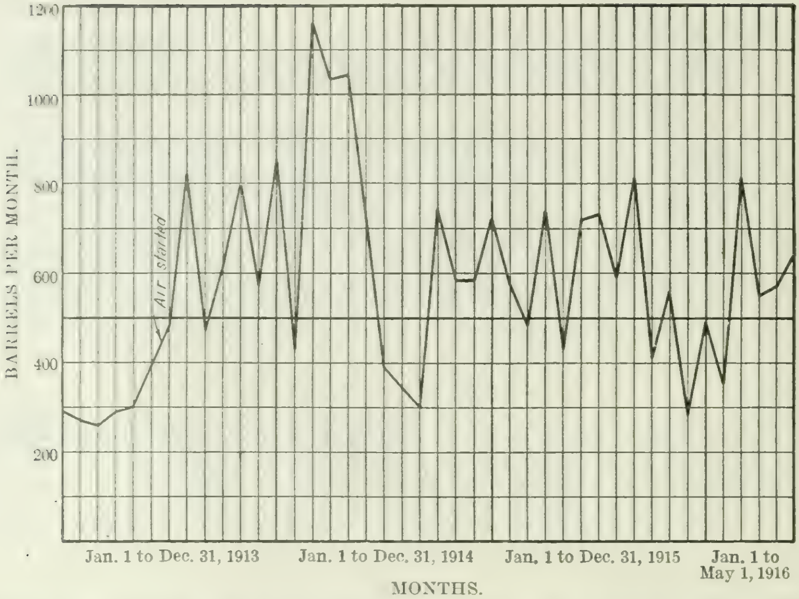

FIGURE 15.—Production curve of property No. 4, Table 4. This is part of the Joy farm, Morgan County, Ohio, and was first drilled in 1861.

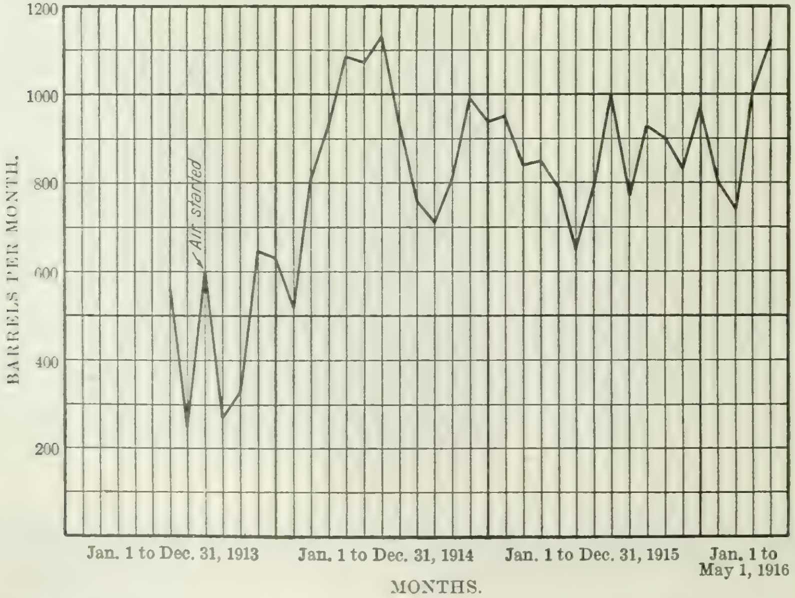

FIGURE 16.—Production curve of property No. 8, Table 4. It took six months to increase production, but at the end of three years the production was still increasing. The upper part of the sand is very coarse and formerly gave large gas flows.

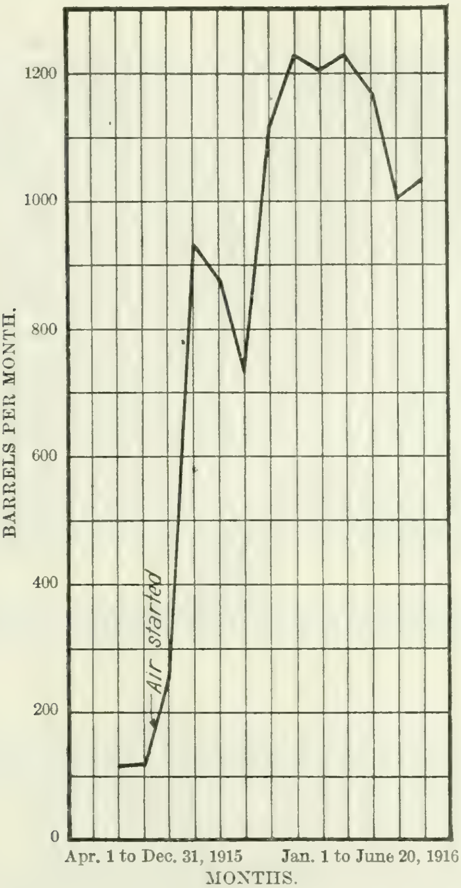

FIGURE 17.—Production curve of property No. 36, Table 4. Within three days production had increased three and one-half times, an unusually large increase. The wells were drilled in the latter part of 1910.

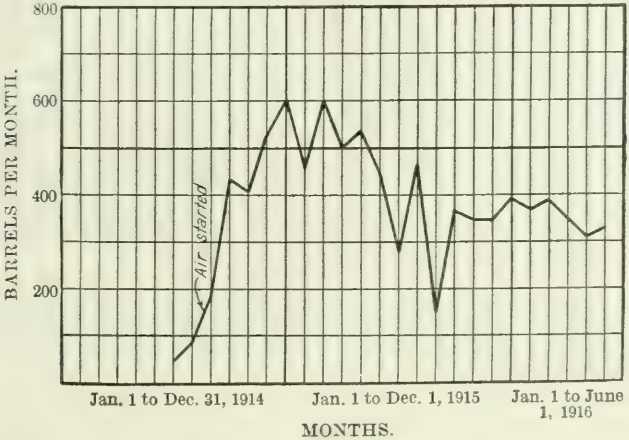

FIGURE 18.—Production curve of property No. 16, Table 4. Oil sand is fine, requiring pressure of 160 pounds, yet the production was increased rapidly.

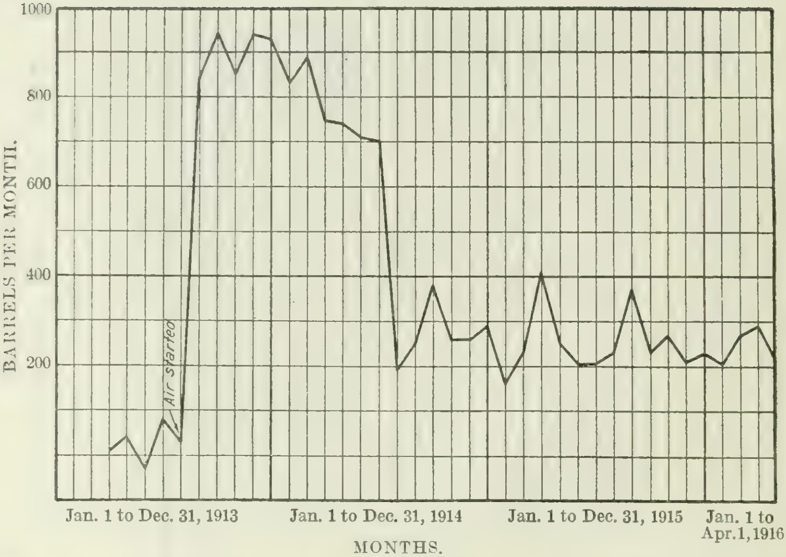

FIGURE 19.—Production curve of property No. 5, Table 4. Production is from the Macksburg 500-foot sand, in which a number of failures have been reported.

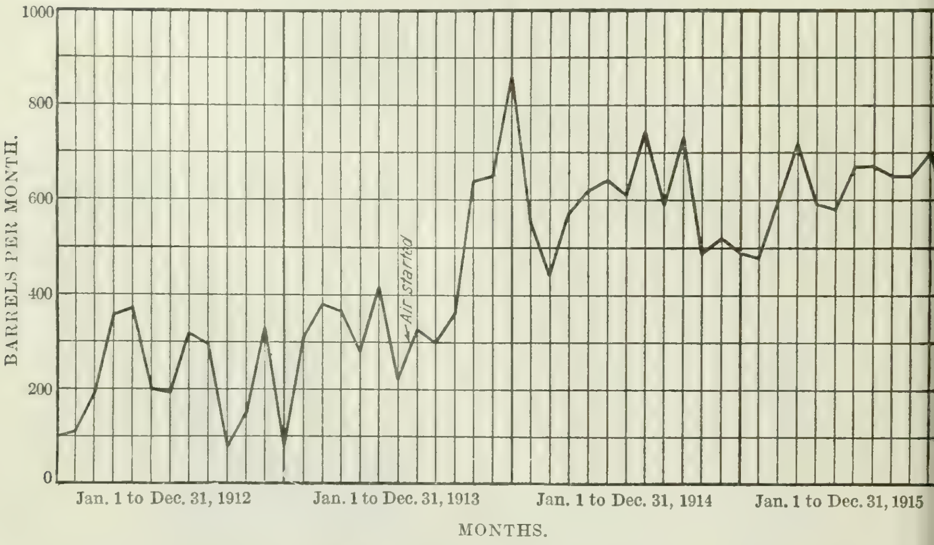

FIGURE 20.—Production curve of property No. 6, Table 4. It took three months to influence production. The sand is fairly tight and the wells had been gas pumped for many years. Almost no decline was shown after compressed air had been used more than two years.

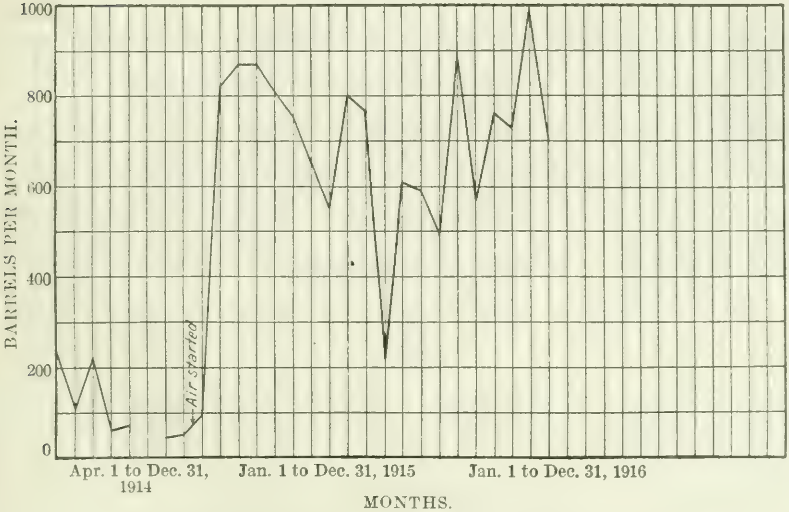

FIGURE 21.—Production curve of property No. 14, Table 4. Shows a rapid and large increase in production. Note increase for the last nine months.

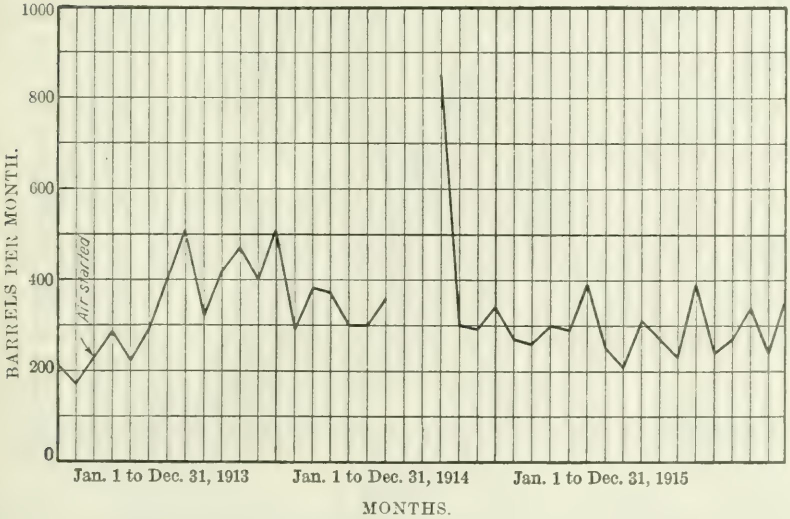

FIGURE 22.—Production curve of property No. 3, Table 4. The increase of production has been comparatively small, but has been maintained with little decline.

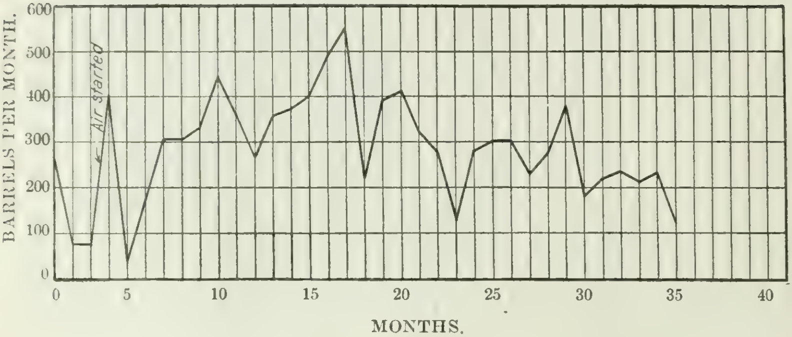

FIGURE 23.—Production curve of property No. 11, Table 4. Oil sand is tight, requiring pressure of 240 pounds. It took four months to increase yield and the increase has been only moderate.

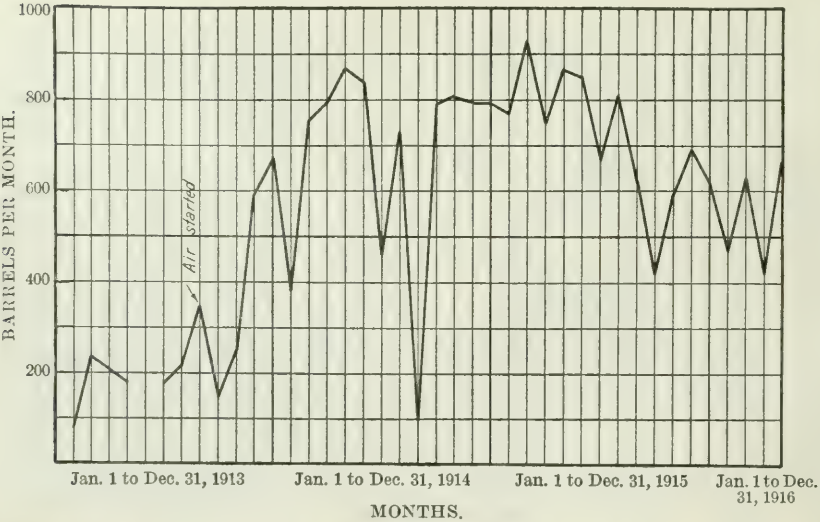

FIGURE 24.—Production curve of property No. 7, Table 4. The property had been gas pumped six years and the first wells were drilled in 1861.

EFFECTS OF THE PROCESS ON RECOVERY.

On some properties using the process no appreciable increases in production have been reported, although even the majority of these have shown some increase. On at least two properties the production has been increased ninefold, and still larger increases have been reported, but the writer did not find opportunity to substantiate them. The records of 32 properties, including several where the process was only partly successful, give an average increase of three and one-half times the production at the time the process was started, this increase being sustained for periods of several months or more. The productions of 14 representative properties are shown in figures 11 to 24.

As the operating expenses usually are not increased proportionately with the oil production, profits show a relatively greater increase than production. On some of the properties where the process was installed the yields had so closely approached the economic minimum that producing was profitable only during the periods of most favorable market conditions. Favorable results from the process have kept many wells from being abandoned, and caused the rejuvenation of old wells which had been abandoned.

It is not possible to estimate what the total increase in recovery will be because the beneficial limits of the process have not been reached on any property, nor do we know what improvements may be made in future. The benefits may terminate abruptly, or, as is more probable, there may be a gradual decline similar to a normal well decline, as is suggested by some of the production curves. On the whole the future is more hopeful than the present results indicate because the process is so new that there are many possibilities of increasing its efficiency.

Although the average increase has been about three and one-half times, the actual productions ordinarily remain very small compared with those obtained in the early lives of the wells, for previous to the use of the process productions had dropped to very low rates, being on most properties less than one-fourth barrel per well daily. While the increases are relatively important, they would have to be maintained for long periods before the percentage of increase in total recovery would be large. For example, the property represented by figure 11 marketed a total of 191,045.65 barrels of oil during the period of 13½ years covered by the production curve, which, however, does not include the first 8 years of the life of the property. Of this total about 35,000 barrels, or 18½ per cent, is attributed to the increase caused by the process during the 5 years it has been used (see fig. 11), but it must be noted that not only is the production increased but the abandonment of small wells, otherwise unprofitable, is prevented, and that the whole property is not equipped with the process. In order to double the natural production since 1903 the present rate would have to be maintained for about 20 years longer, and to double the production for the entire life of the property would require a length of time practically beyond consideration. The production curve of this property and of most of the others where the process has been used long shows a tendency to decline, which if unchecked will make a doubling of total recovery not to be hoped for on the average property in the Appalachian field; and, in fact, it is far more likely that if the future does not show greater efficiency the total increased recovery on the average property can not reach 50 per cent. Even these indefinite estimates are based on the assumption that the benefits of the process will continue for long periods, for which there is no adequate proof at the present time, but they serve to show the limiting factors as the process has so far been conducted and that if the recovery to date by ordinary means actually has been but a small proportion of the underground supplies, as is indicated by the data submitted previously, production would have to be continued almost indefinitely before even half of the unrecovered oil could be extracted. The indications are that the process as now conducted is far from perfection, but nevertheless it will play an important part in prolonging the supply of oil.

In the laboratory experiments the ultimate recoveries by the continued passage of air through the sand were large, especially with the light eastern oils, but much of the oil extracted toward the end of an experiment required such large volumes of air that similar recovery in the field would obviously be impracticable. However, if the recoveries from the fields by the usual methods have been no greater than indicated by the facts submitted previously, a wide margin still seems to lie within the practical limits of recovery, provided the efficiency in the field can be brought reasonably near that in the experiments. Judging from the experimental data, it may be possible to prolong production at gradually diminishing rates for many years if economic conditions permit.

DISCUSSION OF THE PRODUCTION CURVES.

The production curves on properties employing the process, shown in figures 11 to 24, are based upon authentic records of oil shipments. The sharp irregularities in production between months are caused largely by the time of the month shipments were made, and are due only in a less degree to the variations in the well productions. During the period August 1, 1914, to October 1, 1914, production was arbitrarily curtailed by the pipe-line companies who refused to ship the full capacity of the wells because of glutted market conditions.

The curves are typical of their several types, and are fairly representative of the properties where the process has been so far successful that its use has been continued.

Especial interest is attached to the curves covering periods of two years and more. The longest period is five years, shown in figure 11. Where the records cover a sufficiently long period to show the nature of the curve, it may be observed that maximum production is usually reached 6 to 18 months after the process has started, after which there is usually a gradual decline. Figures 11, 14, 15, 18, 19, 22, and 24 are of this character, while figures 16, 20, and 21 show little or no decline, and in figure 16 the maximum production has not been passed, although the process has been in use three years. These records are too few to permit general conclusions, and it is possible that the tendencies noted in these records will not be substantiated when more complete data are available in later years. Under natural conditions, the operator has little control over the factors of oil production, but in the Smith-Dunn process some of the conditions are under his control, and consequently there is more chance for him to improve the process, which will considerably affect the productions of the wells. Originally there was in the sand a limited amount of gas which expelled the oil, and was finally exhausted, but in the Smith-Dunn process the expulsive force is being put into the oil sand continuously, and may be increased or decreased both in volume and pressure at the will of the operator. For this reason it can not be presumed without evidence that a well will decline under this process in the same way as under natural conditions. Production may continue for a period and then end abruptly, or, as is more likely, it will gradually decline unless checked by changes in the way of operating the process.

EFFECTS OF THE AIR ON THE QUALITY OF THE OIL.

Some apprehension has been expressed that the air pumped into the sand would unfavorably affect the quality of the oil, but repeated inquiries disclosed only one complaint by the producers on this account, and the general opinion held is that the oil is livelier, of better quality, and is even claimed to be lighter than formerly. Analyses of oils affected by the air do not show any noticeably unfavorable alterations in the oils.

The apprehension is doubtless caused by observing the deterioration of oil when exposed at the surface. Deterioration is caused principally by the lighter parts of the oil evaporating when exposed to the atmosphere, but this would also occur were the atmosphere composed of natural gas instead of air. With the underground conditions the effect of forcing dry gas through the sand would be the same as forcing the air through the sand, except that there is some chemical reaction between the oxygen in the air and the oil, there being a tendency to oxidize the unsaturated hydrocarbons. The statement that the oil has been lightened has been made repeatedly and upon good authority, but the writer was unable to establish this definitely on any single property because he had no records of the gravity of the oil at the time the process was started.

No increased troubles from the deposition of paraffin in the sands was reported by the operators using the air on their properties, whereas in many instances it has been reported that the increased pressures from the air have forced much waxy material from the wells. If there is a tendency for the expanding air to cause refrigeration and deposition of paraffin, as feared by some oil men, it appears to be counteracted by the increased pressures which force the paraffin out instead of letting it accumulate in the pores of the sands as formerly under the weak gas pressures. The presence of the air under pressure in the sand allows the use of methods for removing the paraffin from the sand about the hole that could not be used before, as it will force out the waxes as soon as melted, instead of letting them seal up the sand, as would happen were there not a strong gas pressure in the sand.

EFFECTS OF THE AIR ON THE WATER.

The forcing of air through the sand usually increases the volume of water produced with the oil, but this increase is reported to be proportionate to the increase of oil, so that the ratio of oil and water produced remains approximately the same. In some wells the volume of water made fluctuates, and instances have been reported where a well will make water almost exclusively for a while, to be followed by a period when little water accompanies the oil. Complaint seldom has been made by the users of the process because of the increase in water, as it has been proportionate to the increase in oil.

The only serious complaint made was where the process was used near Lima, Ohio, in wells producing from the Trenton limestone. Producers in this district report that normally 30 to 40 barrels of water accompany each barrel of oil produced by the ordinary methods. When the air was forced through the sand the volume of water became so great in many wells that the users became discouraged and stopped the process. Whether the process will affect other fields similarly, where large quantities of water are present, is not known, because the character of the oil-producing rock, a porous limestone, is not the same as for oil sands.

A number of users of the process have reported that the water corrodes the tubing and pumping equipment more than formerly. The following analysis of a sediment produced with the oil indicates that there is some basis for complaint, for presumably the iron in this sediment is derived from the corroded equipment in the well:

Analysis of sediment interfering with pumping apparatus on oil property near Oil City, Pa.

[Analysis by W. C. Cope, Bureau of Mines.]

Constituent.		Original.	Corrected.
Moisture	per cent	4.55	4.51
Oil	do	17.32	17.21
Sodium chloride	do	5.52	5.48
Calcium sulphate	do	1.70	1.69
Calcium carbonate	do	5.63	5.59
Silica	do	1.21	1.20
Carbonaceous material	do	1.30	1.29
Iron rust[a]	do	63.57	63.03
		100.80	100.00
Ferric oxide[a]		55.41	54.95
Carbon dioxide		1.21	1.20
Water		6.95	6.88
		63.57	63.03

When the water is aerated by the air passing through the sand its power for corrosion is increased. The unfavorable effect will depend largely on the character of the water, and if it has corroded the equipment previously, the trouble may be aggravated, but if it has not, it is not likely that the air will cause trouble. The cost of producing oil has been increased on certain properties because of this trouble, principally by the formation of a sediment which gets into the pumps and cuts the cups, but relatively the effect has not been serious.

PUMPING TROUBLES OFTEN INCREASED BY USING THE PROCESS.

Not only does the air sometimes increase the formation of sediments by the corrosion of the iron in the well, but it may bring more floating sand and other sediments into the well which will increase pump troubles and make it necessary to pull the wells more frequently than before. On many properties the additional trouble is negligible, whereas on others it has considerably increased the expense of operating. Less trouble has been experienced from hard, tight sands, and the previous condition of the well has proved to be a very important factor, for it has been generally noted that those operators who clean their wells with unusual thoroughness have had less trouble than their neighbors. Pump troubles are reported to diminish with time on those properties where the process has been in use long enough.

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[a] A hydrated ferric oxide containing some carbonate.

Probably pump troubles have been caused not only by the increase of sediments but by poor pumping equipment inadequate to handle the increased production. On many properties where the process has been employed the equipment had been allowed to deteriorate and the wells had not been kept in condition because the yield had become so small that the producer could not afford to make any but essential repairs or replacements of equipment.

EFFECTS OF THE AIR ON QUANTITY AND QUALITY OF GAS.

In all instances reported, the volume of the gas has been increased considerably. On many properties when the compressors were first installed there was not sufficient gas to run the plant more than a short period during each day, but as the air was forced into the sand the quantity of the gas increased so that soon the plant could be run to its full capacity. On a number of properties insufficient gas formerly had made it necessary to purchase gas or gasoline for fuel to furnish power, and on one property coal was burned under boilers for pumping the wells. Some of these properties previously short of gas now have an excess that is being burned in flambeaus.

The increase in quantity is largely due to the air which passes through the sand and becomes mixed with the gas, but there must also be an actual increase in the quantity of petroleum gases, as the air-gas mixture supplies more power than the gas formerly produced.

The compositions of the air-gas mixtures vary in the percentages of air, of gasoline vapors, and of the other petroleum gases. The quantity of gasoline vapor is roughly proportionate to the percentage of natural gas. Following are analyses of some air-gas mixtures:

Results of analyses of air-gas mixtures.

Constituent.	No. 7841[a].	No. 7846[b].	No. 7844[c].	No. 8433[d].	No. 8436[e].
Carbon dioxide (CO_2)....per cent..	1.07	1.20	0.70	4.60	7.00
Oxygen (O_2)....do....	19.40	4.30	16.80	12.90	.50
Nitrogen (N_2)....do....	76.69	73.70	78.00	75.60	2.60
Methane (CH_4)....do....	....	....	....	....	64.20
Ethane (C_2H_6)....do....	....	....	....	2.50	25.70
Propane (C_3H_8)....do....	....	16.40	....	4.40	....
Butane (C_4H_{10})....do....	2.84	4.40	4.50	....	....
Gasoline—pints per 1,000 cubic feet..........	1.44	13.90	3.40	....	....

[a] Air-gas from property No. 6 (Table 4); very lean, burns without visible flame; is not being used.
[b] Air-gas from property No. 31 (Table 4); fairly rich, being used in gas engine.
[c] Air-gas from property No. 5 (Table 4); being used in gas engine.
[d] Air-gas from property No. 11 (Table 4); lean gas, being used in gas engine. Gasoline not determined.
[e] Gas from a property near Warner, Ohio, hardly affected by the air. Gasoline not determined.

An operator in the Bradford field reports that the gas from wells 500, 1,500, and 2,150 feet away from an air well showed 76, 26, and 10 per cent of air, respectively. (See fig. 32, p. 115.)

At times the air-gas mixture is so lean it will not burn without the addition of more gas. Evidently the composition of the air-gas fluctuates when the process is first started, for it has been reported that in some instances trouble was experienced in regulating the fuel mixture in the gas engines, though this may be caused by drawing from several wells gas of different composition that does not get well mixed in the lines. After the process has been in use for a while the air gas seems to be more constant in composition and less trouble is experienced from this cause. It would be expected that the continued passage of air through the sand would remove the petroleum gases, so that eventually the gas would become very lean. Evidence from experience is not yet clear on this point, for properties where the process has been in use longest do not always report trouble of this character, whereas some other operators claim that the gas became lean not long after the process was started. It is believed that much of the lean gas is caused by air by-passing or blowing through, and if the operators would exercise more care in regulating the passage of the air through the sand, less trouble would be experienced with lean gas. There is also some evidence that using too high pressure may cause lean gas without adequate benefits from the increase in oil production. The air-gas from the different wells will not be the same in composition, and, if necessary, the gas from some wells can be cut out if too lean. Lean gas ordinarily may be considered as evidence of inefficient expulsion, for if the air were doing its proper quota of work it is hardly likely that it would come through the sand too lean to use.

The dilution of the gas makes it necessary to adjust the air and the gas intakes on the gas engines. The gas intakes must be enlarged in proportion as the gas gets lean, and the air intake must be reduced correspondingly. At times the fuel mixture will hardly need the addition of any air. The fuel value of the air-gas is less than that of natural gas, and consequently more of the air-gas must be used in the gas engine. As is shown by the analyses on page 80, there is apt to be an abnormal proportion of nitrogen in the air-gas, so that the fuel value is reduced to less than that of a proper mixture of normal air and gas, and thus the power of the gas engine is diminished by the presence of this excess of inert nitrogen, and the actual power delivery of the plant may be considerably reduced below the rated horsepower, which is one reason why a plant should be installed with reserve power.

The excess of nitrogen in the air-gas is probably due to the extraction of oxygen from the air during its passage through the sand rather than to the picking up of nitrogen. The cause for the change of composition of the air is probably due in most part to chemical reactions between the oxygen and the oil, or with other substances underground, but it may also be partly caused by a greater percentage of oxygen being absorbed in the oil when the air is passed through the sand, as suggested by the coefficients of absorption for oxygen and nitrogen in petroleum as given on pages 11 to 13. If this is the principal cause, it shows that vast quantities of oil must be present underground to account for the change in the composition of the large quantities of air being forced through the sands.

EFFECT ON MAKING GASOLINE FROM THE GAS.

The increasing use of the Smith-Dunn process has occasioned inquiries regarding its effect on the making of gasoline from natural gas. So far as it has been used to the present time, the process has diminished the extraction of gasoline. Although the volume of gas is increased, it is apt to be too lean for profitable making of gasoline by compression. A few plants are condensing gasoline from the air-gas by compression, but the majority of the gasoline plants were discontinued where they depended upon the gas from the properties installing the Smith-Dunn process.

As the gas is diluted with air, higher pressures are necessary; also a greater volume must be put through the compressors to obtain the same yield of gasoline; and these facts seriously affect the manufacture of gasoline from such gas. The analyses show, however, that some of the air-gas is still rich enough to make compression profitable, and it has been shown in Bulletin 88[a] that many compression plants have used gas with high air contents, some containing as much as 40 per cent of air. By adding an expansion engine to the equipment and reducing the temperatures, probably it will often be possible to continue to condense the gasoline at the pressures used previously.

According to Burrell, the presence of air will probably affect the extraction of gasoline by absorption methods to a much smaller degree than by compression methods, and it is likely that gases rendered too lean to be treated profitably by compression may be suitable for the absorption process when it is perfected for use in small plants.

PRECAUTIONS IN USING THE AIR-GAS.

The analyses of gas from producing wells on properties using the Smith-Dunn process show that it is a mixture of natural gas, gasoline vapors, and air in varying proportions. Sometimes the mixture is such that it will burn or explode upon ignition without the addition of more air, and occasionally it is too lean to be inflammable. Ordinarily, the air-gas is too rich to be explosive, but Burrell[b] has shown that the limits of explosibility for natural gas range from about 3.5 per cent to 9.5 per cent of wet gas. The mixture of air and gas is more dangerous than pure unmixed natural gas, and this fact should be kept continually in mind in all operations on a property where the process is being used. In spite of the obvious dangers there have been surprisingly few serious accidents.

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[a] Burrell, G. A., Seibert, F. M., Oberfell, G. G., The condensation of gasoline from natural gas: Bull. 88, Bureau of Mines, 1915, p. 68.

[b] Burrell, G. A., Seibert, F. M., and Oberfell, G. G., work cited, p. 97.

The air-gas is commonly used as a source of power in the compressor plants, is sometimes used for domestic lighting and heating on the leases, and at a few plants is used for making gasoline by compression. Burrell[a] has shown that frequently considerable air is also mixed with the gas on properties being vacuum pumped, sometimes 40 per cent of the mixture being air, but the writer has heard of no explosions from this cause in compressors for condensing gasoline. These mixtures are, however, much richer than the average from wells using the Smith-Dunn process. An air-gas within the explosive limits will in all probability be too lean to make gasoline by compression, but the presence of air in the gas should be taken into account and factors of safety adopted accordingly.

A number of reports have been made that the air-gas has been ignited and the flame traveled back in the pipes to the well. Mr. I. L. Dunn states that this has happened several times in his experience, sometimes purposely, but without serious consequences, the pipe and the well not being damaged. One accident was caused by attempting to start an engine with compressed air-gas, which was ignited and reached the charging tank through a leaking valve, blowing it up with great violence. Backfiring into the gas line can be prevented by inserting at the proper point a section of larger pipe filled with small iron tubes or rods that will smother flames by cooling, much as the gauze in an oil safety lamp prevents the mine gases from being ignited by the flame of the lamp.

Occasionally oil will flow from a well by the compressed air. This is reported to have been the cause of one accident. The oil flowed into the gas line and reached the cylinder of the gas engine. By installing a trap in the gas line through which all the gas must pass before reaching the engine this can be prevented.

Apprehension has been expressed of the air-gas in the oil sand becoming ignited and exploding. This does not seem to be a possibility, as the oil sand itself would tend to smother the flame, so that the air-gas in the pores of the sand can not be exploded.

Precautionary measures applicable to properties using the Smith-Dunn process are given in Bulletin 88.[b]

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[a] Work cited, p. 66.

[b] Burrell, G. A., Seibert, F. M., and Oberfell, G. C., The condensation of gasoline from natural gas: Bureau of Mines, 1915, pp. 67–68.

COST OF USING THE PROCESS.

In the following discussion on the cost of using the Smith-Dunn process only the additional expenses caused by its use are considered. These extra costs depend on so many variable factors that it is not advisable to make detailed statements. An endeavor is made, however, to give in a general way the relative expense of installing a plant and the increase in operating expense, as well as to outline the factors influencing the increased costs. Royalties or charges to be paid for patent rights are not taken into account.

COST OF INSTALLING.

At least 80 per cent of the first cost in installing the process is for machinery and other equipment. Under the abnormal conditions prevailing at present the prices of such materials are so unstable that no detailed estimates of cost would be of value. Moreover, the local conditions on each property are so diverse that only the broadest statements would be justified, even were the prices of materials fairly stable.

For equipping a property to use the process there are necessary:

1. A compressor plant, including gas engine, compressor, housing, and accessories.

2. Pipe lines for distributing the compressed air and for gathering air-gas for fuel purposes.

3. The preparation of air wells and the putting of pumping wells and their equipment in proper condition.

The factors governing the size and type of compressor plant have been given previously, and it has been shown that less than 1 to nearly 5 horsepower may be required per well (air and pumping wells), the average being 1.83 horsepower per well. The compressor plants used have ranged in size from 20 to 185 horsepower, though few plants are more than 100 horsepower. Of the equipment, about 70 per cent goes into the compressor plant (including housing and installation), the other 30 per cent being for the pipe lines. The costs of preparing the wells and pumping equipment are not large if the wells and the equipment are in good condition. The cost of installing the process will depend largely on the equipment already in use on the property. If it has been gas pumped, or if a compressor for condensing gasoline has been used, much of the same equipment can be employed in the Smith-Dunn process, or, if not, the cost may be partly compensated by the value of the equipment replaced. The gas engines can often be used for running the compressors, and sometimes the vacuum pumps can be altered and made into compressors if they are of the proper type and size. If the property has been gas pumped the suction lines can be used for air-gas lines, or the pipe can be used for conveying air to the air wells. The air lines have 2-inch to 4-inch mains with 1-inch to 2-inch laterals to the air wells. One-third to one-sixth of the pumping wells are changed into air wells. The items of cost for the air wells may be gained from the description of air wells given elsewhere. In general, the cost is not great and will be largely compensated by the pumping equipment replaced.

The presence of the compressed air on the property supplies a source of power readily distributed over the lease and permits the use of different pumping equipment which may make a difference in the first cost.

Plants installed before the present abnormal conditions arose cost $50 to $150 per well, the average being about $100 per well. Figured in another way, the cost was $30 to $50 per rated horsepower used.

COSTS OF OPERATING.

Inquiries as to the cost of operating properties by the Smith-Dunn process usually brought out the statement that the cost had been increased a little, but not much. Sometimes it was stated that the cost had been increased 25 to 50 per cent, and in one or two instances it was claimed that the expense had been doubled. It was claimed that the expense has been lessened on a few properties by using the compressed air for pumping the oil, the cost being less than when the property was gas pumped.

The items that may increase the cost of operating are: Costs of running the compressor plant, including extra labor where necessary, fuel and water supply, lubricants, repairs and replacements, depreciation and interest on the investment; costs due to the added expense of handling more fluid, and often the increased troubles at the pumping wells due to the sediments brought in by the air. Of these, the chief items of expense are ordinarily the extra labor and the increased pumping troubles.

The extra labor cost depends largely on whether or not the operator chooses to have men stationed at the compressor plants continuously. In general, only one man is used at the compressor plant, it being allowed to run during the night without attendance. Experience has shown that on the ordinary property the liability of preventable damage is not such as to warrant the extra cost of keeping a man at the plant both day and night, where systems are installed for automatic lubrication during periods of 12 hours or more and for stopping the engines should anything happen to the water supply. By these means a saving of $70 to $90 a month for an extra mechanic is effected. Lubrication, repairs, and replacements are not often important items of cost in an efficient plant. It is not often necessary to use other fuel than the natural supply of air-gas, and the only charge which might be made against this item would be the selling value of what gasoline might be recovered from the gas. The cost of water has been nominal in the established plants, and will be elsewhere except in some of the western oil fields, where water may be difficult to obtain. The actual depreciation is not great, but owing to the fact that it is not known how long the production will be benefited, and consequently how long the plant will be in use, a high rate of depreciation should be adopted. The additional fluid which must be handled increases the total operating cost for the property, but decreases the cost per barrel.

The most variable factor in the cost of operating, however, is the trouble in the pumping wells caused by the sediments brought in by the air. On a number of properties the extra expense from this cause has been large, whereas on others it has been nominal. As stated before, pumping trouble is largely due to whether or not the wells have been thoroughly cleaned, and adjoining properties may show entirely different results. Experience on the older properties encourages the belief that usually this trouble will decrease with time.

FIELDS WHERE SMITH-DUNN PROCESS HAS BEEN USED.

Outside of the district in Ohio where the Smith-Dunn process was started, it has been used on several properties near Oil City and Bradford, Pa., also five plants were in use in the Trenton limestone pools of Ohio and Indiana. In southern Kansas it was used in one pool, and in Oklahoma in two pools in the Bartlesville sand, one being where the wells were small and shallow, the other being where the wells were comparatively deep and had been unusually prolific, and still produced large quantities of oil. In California it was experimented with in a small way in a shallow pool producing light oil, the condition being not like those found in most California oil fields.

CONDITIONS UNDER WHICH PROCESS HAS BEEN USED.

To date the process has been applied almost exclusively to wells that had declined to very small productions, the daily yield in many instances being less than one-fifth of a barrel and near the minimum limit of profitable operation. Some of the properties were drilled early in the history of oil producing, some of them dating from the period of 1860–70, and many of the properties had been gas pumped. The depths of the wells range from less than 100 to more than 2,000 feet, and the sands range from fine to pebbly, thick or thin.

The oil is of paraffin base, and, with the exception of some of the oil in Oklahoma, of very light gravity, being 35° to 50° B.

The greatest successes have been obtained in the First Cow Run sand of southeastern Ohio and the Big Lime sand in the district near Woodsfield, Ohio. The First Cow Run sand is usually of coarse, open texture, the wells in it are shallow, and the original pressures were low, but the initial productions were often high, some of the wells starting at several hundred barrels daily. Production has been long sustained, and some of the oldest producing wells in the country obtain their oil from this sand. The Cow Run sand generally occurs in narrow, sinuous "streaks," or as small lenses inclosed in beds of shale.[a] In the Woodsfield district, the Big Lime sand[b] is a true sand, being found in lenses embedded in the lime, and often of small extent, the whole pool sometimes supporting but a few wells. In both the Cow Run sand and the Big Lime sands, the conditions are unusually favorable for quick and decisive results, the sand being of fairly coarse and open texture, while the pools are small and narrow so that the effect of the air has been confined to a small area. The geologic conditions of these districts are sufficiently covered in the publications of the various State geological surveys, and of the United States Geological Survey.

The columnar section, shown in figure 25, from Bulletin 621[c] of the United States Geological Survey, shows the different sands in the district along the Ohio River where the Smith-Dunn process has been used longest and most extensively. The process has been applied to nearly every sand shown. Outside of this district the process has been used in the Rosenberry sand near Emlenton, Pa., the Third Venango sand near Oil City, Pa., the Bradford sand near Bradford, Pa., the Trenton limestone near Lima, Ohio, and Geneva, Ind., and the Bartlesville sand in the Nowata and Boston pools of Oklahoma, and the Sespe sands in Ventura County, Cal.

FAILURES OF THE PROCESS.

Universal and unqualified success is too much to be expected from any process like the Smith-Dunn, especially when new and unperfected. A number of cases have been reported where little or no increase was gained. Failures were caused in the Trenton limestone pools of Ohio and Indiana by the increase of water and the erratic and uncontrollable movements of the air underground. On a few properties the use of air was discontinued and natural gas substituted, not because the increases in production were unsatisfactory, but because the gas from the properties was being used for domestic purposes, or the operators feared it would get too lean.

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[a] Bownocker, J. A., Oil and gas: Bull. 1, Ohio Geol. Survey, 4th ser., 1903, pp. 164–172.

[b] Condit, D. D., Structure of the Berea oil sand in the Woodsfield Quadrangle: U. S. Geol. Survey Bull. 621, 1916, p. 242.

[c] Condit, D. D., Structure of the Berea oil sand in the Woodsfield Quadrangle, 1916, p. 240.

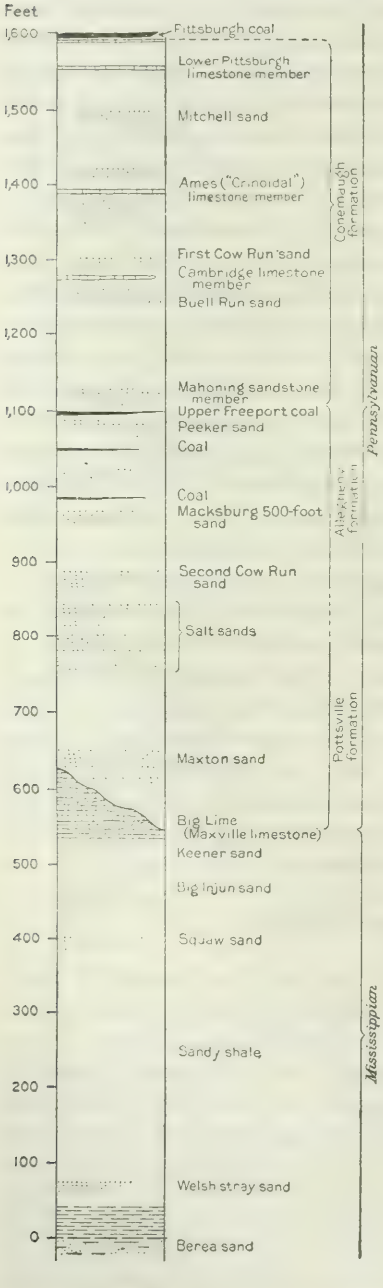

FIGURE 25.—Generalized section of the oil sands in the district around Marietta, Ohio. After Condit.

Undoubtedly many of the failures were preventable and were not due to inherent faults in the process. In at least one case failure was turned into success when the property changed management, and it is likely that other failures could be made successful with proper equipment and experienced application of the process. But until it has actually been demonstrated that a failure was preventable, it must be set down against the process. From inquiries through the fields it is thought that the failures will be less than 20 per cent of the total number of times the process has been used.

From what could be learned of local conditions, failures to appreciably increase production might be traced to some of the following causes: One property never had been profitably productive; on several properties the compressor plants were probably too small, for in one case enlarging the plant made the process successful; in at least one instance the waste of air through old wells, and wells improperly cased, probably caused failure; trying to force the air into too few air wells has been a probable cause, and expecting results too soon has been another (the reader is referred to the production curves as evidence that success may not come until after the air has been in use several months; by-passing and blowing through are reported as causes on a number of properties. In some instances failure can not be traced to any probable cause, and at present must be set down as unexplainable.

A popular opinion has been that the process will fail when applied to tight sands or to deep wells. There are hardly sufficient data to disprove either contention. Up to a depth of 2,000 feet there has been no evidence that the process will not be successful in deep wells where other conditions are favorable. The popular opinion of failure in tight sand has been gained from the facts that a few failures are reported from the 500-foot sand at Macksburg, Ohio, which is said to be a tight sand, and that most of the conspicuous successes have been in the coarse First Cow Run sand and the Big Lime sand near Woodsfield, Ohio. The tight sand requires greater pressure and a longer time to get results, but so far the failure of the tight sands is by no means conclusive. Two properties report using pressures up to 300 pounds; on one the increase is small, but on the other the increase is reported to be three and one-half times. Figures 18, 19, and 23 represent properties where the sand is medium or fine grained, and the pressures used are, respectively, 160 pounds, 110 pounds, and 240 pounds. The wells represented by figure 19 are producing from the 500-foot sand at Macksburg.

POSSIBILITIES OF EMPLOYING THE PROCESS IN OTHER FIELDS.

Despite the diversities of conditions in the various oil fields of the United States, the recovery of oil has seemingly been low everywhere, regardless of the local conditions, or original pressures, depths of well, or of the character of the oil and the character and texture of the oil sands. The cause of decline in all oil fields can be traced to the depletion of the natural gas accompanying the oil; therefore it seems logical that in other fields forcing air through the sand would increase production the same as in fields where the process has been used, although local conditions will determine whether or not it can be used profitably.

The conditions in the Appalachian, Illinois, and Mid-Continent fields are so essentially alike that it hardly seems possible that the process can fail in the other districts if successful in one, but when extended to fields like those of California, Texas, and Louisiana the conditions are so different that it is hardly safe to forecast results, though the experiments with loose sands and California oils gave proportionately more favorable results than the experiments with light eastern oils. For one thing the building up of pressure is likely to cause loose sand to come into the wells, which may neutralize the benefits.

It is interesting to note that in the use of compressed air in California for pumping wells by the air-lift system, Arnold and Garfias[a] have reported that in time the yields from wells so operated show an undoubted decline, whereas wells near by not operated by air have been observed to show an increase. These facts suggest that some of the air from the air lift entered the sand and moved the oil away from the hole toward other wells where air was not being used.

The use of the Smith-Dunn process has been practically confined to old wells which had nearly ceased producing. It would be of interest to know whether the process can be used profitably in wells that have not reached such low productions. It was applied with some favorable results to one property in Oklahoma where the yields were still high, but the conditions were such as to make it difficult to tell whether the use of the process had been sufficiently beneficial to make it worth while. In the Cushing field, in Oklahoma, the accidental admission to an oil sand of high-pressure gas from a deeper stratum temporarily greatly increased the flow of a well which previously yielded about 50 barrels daily. This lends encouragement to the view that the Smith-Dunn process can be used profitably in the early life of a well to stimulate production. This process was tried on a small scale in Ventura County, Cal., the air being forced into a well on the edge of a small and very shallow field for several months, but no appreciable increase in the yields of oil or gas was reported. The oil sand was fairly compact for a California oil sand and the oil had a gravity of 30° B. Why the air did not affect the gas yield can not be explained.

USING NATURAL GAS FOR INCREASING RECOVERY OF OIL.

In using the Smith-Dunn process, results with natural gas seemingly should be as effective in forcing oil from the sand as the use of compressed air, and in addition presents some advantages as compared with using air. The principal advantages offered by the use of natural gas are: The gas recovered from the pumping wells would not be diluted with air and the fuel value decreased; dangerous mixtures of air and gas could not be formed; on properties where natural gas was available in sufficient volume and under high enough pressure no compressor plant would be needed; at times the exhaust gases from gasoline compressor plants could be employed without further compression.

The physical effects of air and natural gas in the sand are much the same. More of the natural gas will go into solution under the same conditions, but whether this fact would prove of importance in practical operations is not known. Apparently the air has not affected the oil unfavorably; and, so far as the writer knows, there would be little choice between air and natural gas from this cause. Theoretically air or any other gas would carry just as much gasoline vapor as natural gas, and where it is hoped to recharge dry natural gas by passing it through the oil sand probably no better effects will be gained than with air.

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[a] Arnold, Ralph, and Garfias, V. R., Methods of oil recovery in California: Tech. Paper 70, Bureau of Mines, 1914, p. 21.

The effect on producing oil wells of admitting natural gas into the oil sand, accidentally or otherwise, has been noted many times in the oil fields. I. L. Dunn states that it was observing such a case that led him to develop the process of using compressed air. An instance in the Cushing field, where the flow of a comparatively new well was greatly increased by natural gas from a deeper sand getting into the oil sand has already been mentioned. It has been reported that gas under natural pressures has been used at various times to stimulate oil flows, and it is also reported that the exhaust gas from gasoline compression plants has been returned to the oil sand, principally with the idea of recharging it with gasoline vapors.

The choice between natural gas and air will usually be decided in favor of the latter because the natural gas will not be available, or only at costs relatively prohibitive. The operating method will be approximately the same, and what has been said about operating with air will apply to the use of natural gas. If the natural gas is not already under pressure, it will have to be put through a compressor plant in the same way as air. By carefully gathering the return gas and putting it through the compressor again, it may be circulated in a closed circuit except for the wastage underground and on the surface, and the quantity used for fuel. By careful operation the wastage should not be large. In the early life of an oil field, while much natural gas is still being produced with the oil, it might be profitable to save the gas and put it back into the oil sand, by this means both accelerating and increasing the recovery of the oil.

INCREASING RECOVERY OF OIL BY WATER DISPLACEMENT.

GENERAL STATEMENT.

Water is practically considered the only available fluid that might be forced through the oil sands to increase recovery, but water—especially fresh water—has usually been considered the arch enemy of the oil man, and the necessity for excluding it from the productive strata has caused the use of casing, packers, cement, and other materials, which have greatly added to the expense of completing an oil well. The general recognition by both practical and technical men of the harm that may result from the entrance of water into the oil sands has caused the passing in all oil-producing States of stringent laws regulating the abandonment of wells and the exclusion of water from the oil sands. The displacement of oil by "flooding" the sand with water has been against the experience and the judgment of the oil men.

Observations that water will displace much of the oil from laboratory specimens of oil sands and that "flooding" often will stimulate yields of oil wells, at least temporarily, have led to much speculation regarding the possibilities of increasing the recovery of oil by this means. These facts were observed early in the history of oil production in the first fields developed in Pennsylvania, and since that time flooding, usually on a limited scale, has taken place in many other fields and under a great variety of conditions.

Often the first intimation in a producing well of an approaching flood is a sudden increase in oil yield without apparent cause. Within a short time the yield may increase many fold, this increase being maintained for periods of several days to several months, and even for many years, as in the Bradford field. The yield, after increasing, is not apt to decline until the water makes its appearance, then the oil is usually quickly and completely cut off by the water and the well becomes valueless. The phenomena of flooding are so familiar to oil men that they regard a sudden increase of oil in an old well, without apparent cause, with suspicion. Frequently, however, the water enters a well without increasing the yield of oil, and, in California, water has been known to enter a well and almost cut off the production in a few hours. Ordinarily, the benefits, if any, are so shortlived and so much less than could have been reasonably expected from ordinary producing methods that flooding in nearly all fields is regarded as a deplorable calamity.

In nearly every instance where flooding has occurred it has been of accidental origin and has not been started intentionally for the purpose of increasing recovery. The causes can usually be traced to defective wells, usually abandoned, or to the encroachment of water rising from the lower levels of the productive formation. Ordinarily, the producers attempt to stop or to localize flooding as soon as discovered. Sometimes a whole field is drowned out, but more often the flooding is stopped after affecting a small number of wells, because the offending wells have been repaired or the sand has been practically sealed up with cavings, or the movements of oil and water have virtually ceased because of the depletion of the water supply. However, in nearly every field will be found some wells that have been drowned out, not by water entering the sand from the well itself, but by water coming through the producing formation. At times the producers have endeavored to take advantage of flooding by drilling in advance of the water or by trying to control the movements of the water by admitting water into wells situated at strategic points. The comparatively few successful attempts have as a rule caused injury to other producers in the same field.

Flooding is excellently described by Carll[a] and other early writers, who note the effects of flooding at Pithole and in other early fields in Pennsylvania. Carll outlined the principles of flooding and came to the conclusion that terminating the life of a nearly exhausted well by displacing the remaining oil with water was sound in theory, but because of the clashing interests in a field, the difficulties of controlling the movements of the water, and the dangers of trapping oil it could seldom be applied advantageously. Practically the same views have been held by Huntley,[b] Johnson,[c] and others, who maintain that the fault lies not in the theory but in the attempts to concentrate the oil by flooding without sufficient data as to underground conditions. Among the oil producers themselves, outside of the Bradford, Pa., field, flooding has been regarded with almost universal disfavor because of their many unfortunate experiences.

Unlike the other methods for increasing recovery, a flood passing through the sand leaves the oil not brought to the surface practically irrecoverable. After any one of the other methods has been used the sand can still be flooded or any other process can be employed which may be discovered in the future, but flooding marks the end of the field, and it is not likely that it will ever be practicable to pump out the water or to employ other methods. For this reason flooding should not be employed until it has been demonstrated that it will recover as much oil as other methods and as much as can reasonably be hoped for from future discoveries.

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[a] Carll, J. F., The geology of the oil regions of Warren, Venango, Clarion, and Butler Counties: Second Geol. Survey of Pennsylvania, vol. 3, 1880, pp. 256–289.

[b] Huntley, L. G., Possible causes of the decline of oil wells and suggested methods of prolonging yield: Tech. Paper 51, 1913, pp. 9–21.

[c] Johnson, R. H., and Huntley, L. G., Principles of oil and gas production, John Wiley & Sons, New York, 1916, pp. 141–144, 158–161.

The chief exception to the generally unfavorable opinion of flooding held by the producers is in the Bradford, Pa., field, where a majority of the oil men have arrived at a more favorable opinion, so far as local conditions are concerned. Because the Bradford field is almost the only place where flooding is carried on systematically, most of the discussion on the increasing of oil recovery by displacement with water is devoted to results with flooding in this field. Natural conditions seem to be exceptionally favorable at Bradford for the use of flooding and even the most enthusiastic local advocates believe there are few other fields where flooding would be even partly successful, and that what has been accomplished at Bradford can seldom be hoped for elsewhere. The exceptional opportunities in this field for studying the effects of flooding make the experiences and opinions of the Bradford operators well worth recording.

THEORY AND PRINCIPLES OF FLOODING.

Flooding is based on the theory that to remove the oil retained in the oil-bearing formation by capillarity, adhesion, and frictional resistance after the exhaustion of the gas, something must be introduced to displace the oil and refill the spaces it had occupied. Water is introduced into the field to displace the oil from the pores in the oil-bearing formation, concentrate it ahead of the flood of water, and force it into pumping wells through which it is brought to the surface.

Huntley[a] gives the following summary of the principles of flooding, to which the writer has made some additions, in brackets:

> The main factors affecting the flooding of an oil-bearing formation may be summarized as follows (adapted from Carrl):[b]
>
> (*a*) Time of flooding—whether early in the process of operations, while yet a large percentage of oil and gas remains unexhausted, or at a later period after the supply has suffered from long-continued depletion.
>
> (*b*) Composition and thickness of the formation [whether loose or consolidated], whether regular and homogeneous throughout or composed of fine sand interbedded with irregular layers of gravel, in places lying near the top and in places near the bottom.
>
> (*c*) Position of the pool—whether flat, as on a structural terrace, upon a monoclinal slope, upon the crest of an anticline, or at the bottom of a syncline [and what the angle of dip is].
>
> (*d*) Shape [and size] of the area being flooded.
>
> (*e*) Position [and number] of the point[s] at which water is admitted in reference to the situation of surrounding wells still pumping oil.

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[a] Huntley, L. G., Possible causes of the decline of oil wells and suggested methods of prolonging yield: Tech. Paper 51, Bureau of Mines, 1913, p. 20.

[b] Carrl, J. F., The geology of the oil regions of Warren, Venango, Clarion, and Butler Counties: Second Geol. Survey of Pennsylvania, vol. 3, 1880, p. 265.

(*f*) Height of the column of water obtaining admittance.

(*g*) Duration of the water supply. It will readily be seen that a temporary flooding in comparatively fresh territory, as from the drilling of new wells without casing and from the overhauling of old ones having the seed bag attached to the tubing in the primative way, must necessarily be a different affair from a flooding caused by a permanent deluge through unplugged and abandoned wells in nearly exhausted territory.

(*h*) [Character of the oil and of the water].

These factors are considered in detail in Huntley's paper and some valuable facts are given. The same subject is also considered briefly in Technical Paper 130.[a] Some phases of the subject have also been treated in previous paragraphs of this report.

Until the oil-bearing formations have been partly exhausted, little water can enter and extensive flooding is seldom possible. It can not be held that the water entering the sand displaces an equal amount of oil, that is, barrel for barrel, for part of the water occupies pores from which the oil has long since been removed, nor does the water force out and displace all the oil remaining in the pores.

The water entering the productive formation may be the water generally found in the same formation at lower levels which rises into the productive parts upon the escape of the gas and part of the oil that previously had held the water in place, or it may enter from other strata and even from the surface through defective wells. It may be in comparatively small quantities, which can be produced simultaneously with the oil; or it may enter the sand in such large volumes that either the wells can not be pumped at all or not profitably. The water may enter for only a short period or indefinitely. Most oil wells produce some water, and in the eastern and middle western fields often a relatively large part of the fluid produced during the later life of the well consists of salt water. In the eastern and the Mid-Continent fields, where the oil is light and of paraffin base, small quantities of salt water are generally considered more beneficial than injurious, as the producers believe it flushes the oil from the sand and lessens the deposition of paraffin that would clog the pores and obstruct the passage of the oil. In California, however, the experienced producers regard even small quantities of salt water as detrimental.

HOW A FLOOD SPREADS THROUGH AN OIL-BEARING FORMATION.

If the oil sand were level and the conditions were uniform in all parts, the water entering from one well would spread in an ever-widening circle whose area would increase as the square of the radius. If in the first year the water reached 100 feet from the well, in the next year, assuming the same quantity to enter the sand, the water would travel but 41.4 feet farther; in the third year 31.8 feet farther; and each succeeding year the rate of movement would become less and less. But because of a number of factors always or ordinarily present the actual decrease in rate is much greater. Among these factors are the increased resistance with the distance penetrated and the quantity of oil accumulated ahead of the water, a tendency for the pores of the sand to become clogged with silt and waxes and for the flooding well to become choked with material caved from the walls of the hole and a probable diminution of the water supply. The result is ordinarily a marked slowing up of the spread of a flood from year to year, unless new sources of water are added. It has been noted many times in the Bradford field that the water may penetrate 200 or 300 feet from a well the first year; but after several years the movement is apt to be not more than 30 to 60 feet yearly, and when a distance greater than 500 or 600 feet has been reached the movement becomes exceedingly slow and almost ceases. But if the water enters the sand, not from one center but from a row of wells, or is encroaching from the lower levels of the oil sand, the advance of the flood does not decrease so rapidly from year to year.

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[a] McMurray, W. F., and Lewis, J. O., Underground wastes in oil and gas fields and methods of prevention: Tech. Paper 130, Bureau of Mines, 1916, pp. 5–9.

A modification of these conditions might be found in a new field. At first, before much oil had been pumped from the sands and while the gas pressure remained high, the water could not enter nor move rapidly, but with the removal of oil and the reduction of gas pressure, the flood could move faster.

As the oil sand is never level nor uniform in all parts, the water does not move equally in all directions nor at a uniform rate through all parts of the sand, and the greater the divergence from these ideal conditions the more irregular in shape will be the area affected. Huntley[a] has described the movements of a water flood as follows:

> When water is admitted in large quantities it tends to flow out in various directions, the greatest flow following the line of least resistance. Owing to the differences in the resistance offered by sands of differing porosities and to varying amounts of gas [or oil] in the rock, this movement of the water and oil in regions of low monoclinal dip—say, 15 to 20 feet to the mile—will extend up the dip as well as down. The movement will be particularly strong in the direction of very porous lenses and toward pumping wells, regardless of the effect of gravitation, the suction created by the pumping wells being sufficient to overcome the relatively slight tendency of the fluid to flow downward. This effect sometimes causes wells situated above the point of flooding to be affected ahead of the water wave and abandoned before those down the dip are affected. As an additional result, the water wave, aided by irregularities in the structure and shape of the pool, will sometimes surround bodies of oil that were originally

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[a] Huntley, L. G., Possible causes of the decline of oil wells, and suggested methods of prolonging yield: Tech. Paper 51, Bureau of Mines, 1913, pp. 18–19.

a part of the pool. Two or three such isolated pools are mentioned by Carll as having been discovered on the outskirts of the Pithole oil pool after the central part had been flooded.

Again, lenticular pebble beds or lenses of unusually porous sand may form pockets in the upper part of an oil sand and may catch quantities of oil, which are retained as the main body of oil advances ahead of the water wave. These pockets furnish the oil in many wells that are entirely surrounded by flooded territory yet continue to produce a little oil along with large quantities of water.

How great an effect the porosity and size of the sand grains and other irregularities in the contents, character, and texture of an oil sand have upon the relative resistance may be gained from the figures quoted from Slichter (see p. 18) and from the experiences gained in forcing air through oil sands in the Smith-Dunn process.

Not only will the line of least resistance be down the dip and toward the pumping wells through the most coarse and porous parts of the oil sand, but will be through the parts containing the least oil. A part that formerly has contained only gas, provided the texture is not too tight, will afford less resistance than a part where much oil remains.

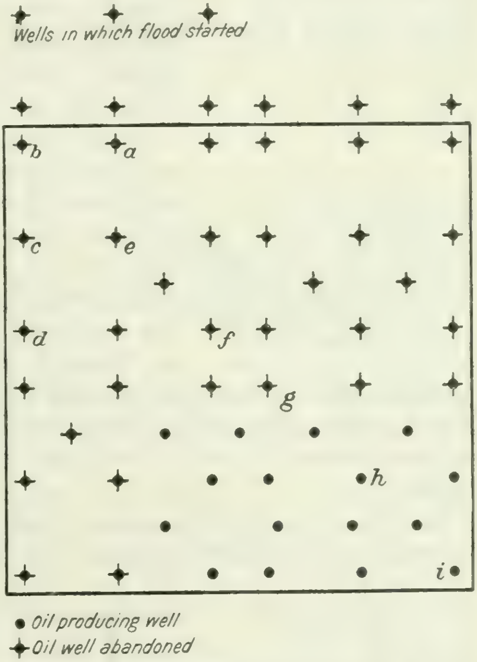

FIGURE 26.—Diagram showing movements of water on oil property in the Kane field near Bradford, Pa.

These differing conditions in the oil sands that affect resistance are at times more important than a considerable slope in the formation, as is shown by a case reported from the Coalinga field, California, by M. J. Kirwan, State deputy petroleum and gas supervisor.[a] In spite of a dip of 27 feet to the hundred (over 1,500 feet to the mile) the water traveled faster along the level and up the slope of the formations. The same case also shows the irregular movements of water spreading through the sand from one well.

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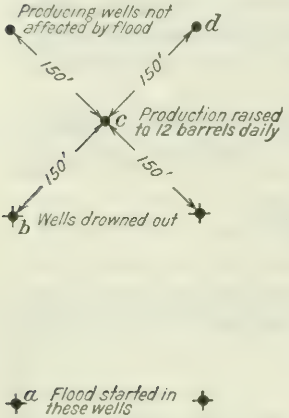
[a] First Annual Report of the State Oil and Gas Supervisor of California for the Fiscal Year 1915–16, Bull. 73, pp. 110–115.

The irregular movement of a "water drive" is also illustrated in figure 26, the information being supplied by one of the largest and most responsible operators of Bradford, Pa. The flood took place on a property in the Kane field near Bradford, Pa., production being obtained from the Kane sand which underlies the Bradford sand by 265 feet. The flood started at several well locations from the property and advanced gradually, affecting wells *a* and *b* first, the water coming in and drowning out the wells almost simultaneously with the increase in production, so that little benefit was obtained. Wells *e* and *c* were affected next, well *c* being drowned out quickly, while well *e* produced a large quantity of flood oil and was not abandoned until long after other wells near by had been drowned out. Wells *d*, *f*, *h*, and *i* were affected progressively, wells *d* and *f* having been drowned out, while wells *h* and *i* were still producing, but the water passed entirely around well *g*, affecting all the other wells near by, although well *g* was not affected until recently, when it began to make much water and a little more oil than formerly. At the time this was written, of the 48 wells on the property 16 were still producing.



Producing wells not affected by flood
d
150'
150'
c
Production raised to 12 barrels daily
150'
150'
b
Wells drowned out
a
Flood started in these wells

FIGURE 27.—Sketch of a group of wells in the Bradford, Pa., field, showing how short a distance wells are affected ahead of a water drive.

As the water will travel most quickly through the lines of least resistance it will advance through one layer in the sand and drown out the wells before they can be benefited from the oil that has accumulated in the less porous parts of the sand which will always lag behind. This principle is illustrated in figure 28, which is the probable explanation of the actual conditions shown in figure 27. It also

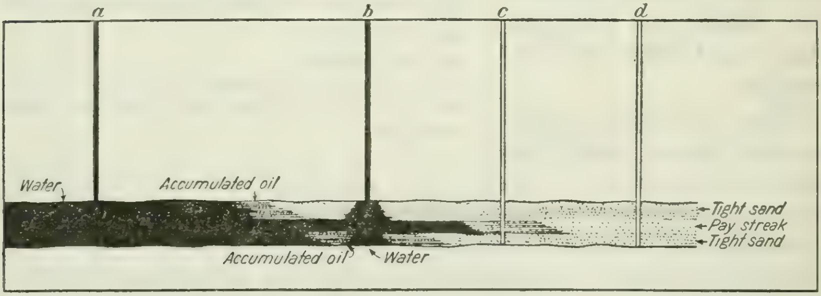


FIGURE 28.—Section through wells *a*, *b*, *c*, and *d* in figure 27, showing probable conditions in the oil sand being flooded.

explains the conflicting reports of conditions in wells drilled into flooded areas in the Bradford field, where some operators report that the sand was found waterlogged from top to bottom, as in well *a*, figure 28, whereas others found that only a minor part of the sand contained water, the rest of the sand showing oil, as between wells *b* and *c*, figure 28. Evidently the water, when it enters the oil sand, does not stratify with the oil making a level surface between the two fluids, for then there could be no such condition as is shown in figure 27 and as has been reported in other instances, where of three wells drilled within 150 feet of each other in a thick sand lying practically level, one is flooded out, one is producing flood oil, and the third is not affected. Either the water advances in a wall, the front of the flood being nearly perpendicular, or, as is most likely, it travels fastest through a comparatively thin layer in the sand in the manner illustrated.

In view of the many variable factors influencing the movement of the water, it is not surprising that the rates at which the water travels and the area affected by one well vary widely in the different oil fields of this country. It must not be inferred that the slow movements of water shown by experience in the Bradford field are usual, for they are evidently unusually slow and restricted even for the eastern fields. In contrast the water has been known to travel through the sands in California fields distances in days that it would take years to advance in the Bradford field, and one well has been known to seriously injure large areas.

An instance of water movements through oil sands under conditions different from those in the Bradford field is reported by F. B. Tough, of the Bureau of Mines. In a part of the gusher district in the Midway field of California, where the wells are 3,000 to 3,500 feet deep, the oil of a specific gravity of 27° B., and the sand fairly fine grained, the pumping of one well that was badly troubled by water would decrease the proportion of water in another well situated farther down on the dip and 400 feet distant from 70 per cent to 2 per cent and raise the oil production from 60 barrels to 130 barrels daily within 36 hours. If pumping were stopped in the first well, the water would flow through the sand and cut off the production in the second well in 36 to 48 hours.

Similar cases have been reported elsewhere in California fields, the general experience being that water travels quickly, irregularly, and in large volumes through the oil sands. From the Coalinga field, Kirwan[a] reports an instance where the edge water encroached upon the extraction of the oil and relief of gas pressure higher up the dip in the oil sand, about 800 feet in 6 years. But in the case previously cited where flooding was caused by a defective well, another well about 1,000 feet distant was affected within 5 months.[a]

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[a] Op. cit., p. 83.

RELATION OF GEOLOGIC STRUCTURE TO FLOODING.

Where the dip is low its effects on the movement of water are likely to be less than that of other factors, as at Bradford, but where steep it may be the controlling factor and cause practically all the water entering the oil-bearing formation to flow in one direction. In such a case there will be a tendency for the water to follow channels, and there is not likely to be much increase of oil production in wells affected by the flood unless the water is introduced at the lower edges of the field so that it must rise up the dip. Theoretically the water should always be introduced in this way, because it is heavier than the oil, thus forcing the latter toward the higher parts of the oil-bearing formation, but the movements are at times so slow and so little controlled by the dip that sometimes it would be impractical to flood a large field in this way, as in the case of the Bradford field.

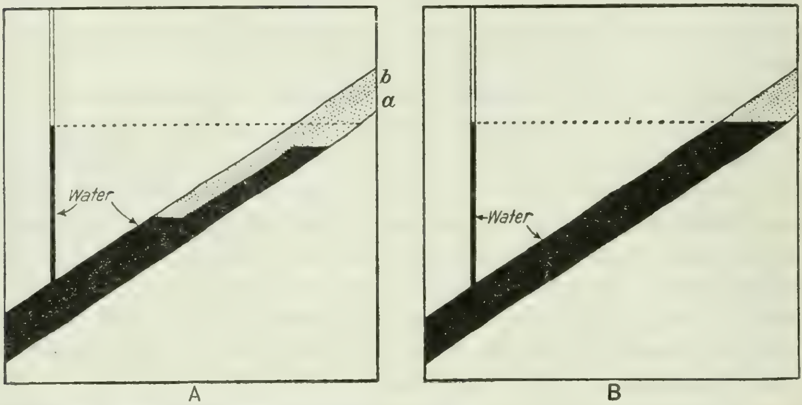

FIGURE 29.—Diagram illustrating the theory of flooding up the dip. Water is let into the well and rises up the dip, progressing faster and reaching equilibrium first in the layer of least resistance, *a*, as shown in A. If the water column in the well is not increased, the water will also rise in the tight part of the sand, *b*, and reach equilibrium, as shown in B. By carefully restricting the quantity of water entering the well and the height of the water column, it is sought to make the water rise equally in all parts of the sand.

It has been suggested that the troubles arising from the varying rates of movement of the water through the different parts of the sand caused by the diverse conditions might be overcome by letting the water rise up the dip. This principle is illustrated in figure 29, which represents the simplest conditions. If the water column in the well were maintained at the same height, the water would rise through the sand up the dip till it stood at the same level, but would reach this level first in layer *a*, which offers less resistance than *b*, as shown in A. By introducing the water no faster than it would advance through *b*, the water should advance on a level through the sand as shown in B, so that the trapping of the oil in the tighter parts of the sand would be lessened.

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[a] Op. cit., pp. 110–115.

In the practical application of this principle, the trapping of oil would be difficult to avoid even where flooding was carried on with complete cooperation among the producers of the field, and after the most painstaking investigations of the underground conditions had been made. The first problem that suggests itself is how to determine how fast the water is moving through the different parts of the sand, and the rate at which the water should be fed into the sand at each well to avoid the faster progress of the flood through some parts than through others. If the sand were level this irregular advance could not be prevented no matter how slowly the water were let in, for the principle is based upon keeping an approximate balance of pressure between the water that has risen in the sand and that standing in the well (see fig. 29). If the sand had a low dip, say 20 feet to the mile, and was 40 feet thick, the water would have to advance 2 miles along the bottom of the sand before it would strike a level through the sand and reach equilibrium in all parts. To prevent irregular advance of the water and trapping of oil under such conditions of relative dip and thickness of sand, which approximate the conditions in most fields east of the Rocky Mountains, only a very low column of water could be held in the well and consequently the advance of the water in a field like the Bradford, where the advance is slow under water pressures of 1,000 feet or more, would make flooding on this principle impracticable. Where the dips are relatively steep it would still be necessary to use very low pressures. It must be remembered that along a line at right angles to the dip, the bed lies flat and that the water entering from a well if it can not go down the slope, will move laterally rather than up the dip, and in these directions the conditions outlined above prevail even where the dip is steep. For this reason the flooding would have to be started along a row of wells and there would be difficulty in regulating the advance from each well because of the varying resistance and dip of the sand from place to place.

The rise of the water being from the bottom of the sand upward, it would be necessary to plug the bottom part when the water reached the well; otherwise it would rise into the well and increase producing costs, or drive the oil back into the sand. The bottom plugging of the hole would have to be done periodically with the rise of the water.

For these reasons the writer believes that attempts to avoid the trapping of oil by flooding up the dip can seldom be successful in practical operations.

EFFECT OF HYDROSTATIC PRESSURE ON FLOODING.

If the water is under high hydrostatic pressure more water will enter the sand and it will move faster than if the hydrostatic head is low, but there has been some confusion in regard to the pressures actually exerted by the water upon the oil, and the effects that pressure has in displacing the oil from the sand. At the bottom of the well where the water enters the sand the full hydrostatic pressure of the column of water standing in the hole is exerted, but in the oil-bearing formation the actual pressure exerted becomes less and less away from the hole in accordance with well-known laws governing the loss of head or pressure of a fluid flowing through pipes or sand in which there is frictional resistance. At the edge of the flooded area, where the oil is being displaced and driven ahead of the water, the actual hydrostatic pressure exerted may not be large, neither is the hydraulic force of the moving water much, for after the flood has extended for a distance of several hundred feet from its center the advance often becomes very slow. For example, at a rate of 100 feet yearly, which is more rapid than the average in the Bradford field, the advance is less than 3½ inches daily, which is about one-third the rapidity of the movement of the hour hand on the ordinary-sized watch. At such a slow rate the water passes through the sand quietly, and is not turbulent nor accompanied by agitation. In fields where the water travels most rapidly, as in California, production is not often increased by flooding.

TRAPPING OF OIL BY WATER.

How oil may be trapped by water has been brought out in former paragraphs. It may be caught by irregularities along the top of the oil sand, or by barriers in the oil-bearing formation. (See fig. 2, p. 15.) Because of the diverse conditions, the water advances more rapidly through some parts of the oil-bearing formation, surrounding or making unavailable the oil in the other parts. (See fig. 28.) The layers in the oil sand are seldom uniform for long distances along the bedding, as assumed in figure 28, but are variable even in the most uniformly bedded sands so that one layer may be porous in one place and tight in another, or the partings present in one place may be absent in another; consequently the water will now and then cross from one layer into another ahead of the oil and trap it, or the oil may be driven into pockets and held there. In addition, the converging of floods starting from many centers and the tendency for the water to advance to and drown out producing wells ahead of the general front of the flooded area greatly increases the quantity of trapped oil. The more irregular the conditions in the oil-bearing formation, and the more numerous the centers of flooding, the less complete will be the recovery of oil. Once the water reaches a well, production seldom can be continued because usually the water is in quantities too large to permit profitable operation, and the oil remaining in the sand becomes practically irrecoverable.

INCOMPLETE DISPLACEMENT OF OIL BY WATER.

It has been shown how bodies of oil may be trapped in the oil-bearing formation because of the irregular structure. Next may be considered how completely the oil is displaced from the pores where conditions are fairly uniform in the formation. The principal conditions in a sand being flooded are: The water moves slowly, without agitation; the pressure may be high at the place where the water enters, but is likely to be low at the front of the flooded area, where displacement of oil is taking place; ordinarily temperatures will be somewhat higher than the average surface temperatures; the water may be fresh or salt; the oil may range from the lightest paraffin oils to the heaviest asphaltic tars; the oil-bearing formation may be fine tight sand, loose gravel, or vesicular dolomitic limestone.

A few elementary experiments conducted under conditions far more favorable than could be hoped for in oil sands underground, indicate that much of the oil may not be removed by passing water through a sand. In the experiments described on page 23, fresh water at 70° F. was passed through tubes of well-drained sand containing 15 to 53 per cent of the original volume of oil with which it was saturated, yet in only one experiment was there even a color of oil on the water after it had passed through. Likewise no oil was removed from sand from which the oil had been expelled by compressed air or gas, though the water was under 50 pounds pressure. This series of experiments covered a range of conditions from light crude oil from Bradford, Pa., having a gravity of 41° B., to heavy California crude oil with a gravity of 14° B., and two uncemented sands, one medium grained and the other fairly coarse. When water was allowed to rise through sand fully saturated with oil, a slightly larger percentage of oil was retained, but much of the oil displaced was accompanied by a larger proportion of water that would have made production unprofitable in the field. When the sand was partly drained of oil before water was passed through, a much larger proportion of oil was left in the sand, the water showing a marked tendency even in the upright tubes of uniformly packed sand for sidetracking and surrounding bodies of oil. For example, a tube full of the same coarse sand, which would retain a minimum of 15 per cent of the Bradford oil after long draining, was saturated with the oil, 22 per cent was drained out, and water was then allowed to rise slowly through the bottom. Thirty-seven per cent more oil was displaced before water showed at the top, and then an additional 6 per cent with almost ten times as much water as oil. At this point the ratio of water to oil in the mixture increased to 20 times as much water and quickly to 100 times as much water as oil. A volume of oil representing 35 per cent of the capacity of the sand and 45 per cent of the original quantity of oil remained in the sand when the water had reached a proportion that would make production unprofitable in a well.

These experiments show that the water enters the drained pores first, trapping a large proportion of the oil in the undrained pores. In a bed of oil sand partly drained and lying at a low dip, it can reasonably be expected that only a small proportion of the oil will be displaced, even where the conditions are most favorable. From this it can be understood how even at Bradford the recovery by flooding is still but a small fraction of the apparent content of the sand. The recurrent floods, reported by Huntley as taking place periodically at Oil Springs, Canada (see p. 106), yield more oil on each advance and recession of the water, showing that not all the oil is driven into the wells at one passage of the water through the formation.

Johnson has suggested the use of compressed air in conjunction with water in flooding. Johnson[a] says, "Theoretically, it would seem wise to keep the wells farther down the dip open, so that compressed air could be forced in. This air, bubbling through the water-filled sand, ought to disengage some oil that the moving water alone could not dislodge. The accumulation of the air in little domes and pockets in the top of the sand would dislodge oil that had been retained there, so that it would move on up the dip to the pumping wells. Whether this compressed air system will warrant the expense, only actual trial can prove; but judging from the outcome of laboratory experiments, the prospect is promising."

In the Smith-Dunn process the air increased the yield of water quicker than the production of oil, and hence if the air were introduced in large volumes it may be expected to be more detrimental The recurrent floods, reported by Huntley as taking place periodically might aid in displacing the oil from the sand without this harmful effect; but it can hardly be expected to overcome fully the chief practical difficulty in flooding which is caused by irregularities in the sand that influence the movements of the air as much as those of the water.

HOW OIL MAY PASS BETWEEN THE WELLS.

When an oil sand is first opened up the pressure is fairly uniform throughout the oil-bearing formation, and a well drilled into it

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[a] Bacon, R. F., and Hamor, W. A., The American Petroleum Industry, vol. 1, 1916, pp. 430–431.

becomes the center of converging movements of the oil from all parts of the surrounding area; but when the oil-bearing formation is being flooded by water let into one well, the motive force spreads out from the center, the oil accumulating ahead of the water and around the edge of the flooded area. As the flood advances the oil directly in the path of the water is forced into producing wells, but there is little force acting to bring the oil into the well from either side along the front of the flood. This condition differs essentially from the original one, for there is now no force to bring the oil in from all directions toward the pumping well, the force being applied practically in only one direction, so far as each producing well is concerned, so it is very likely that a producing well gets the oil from only a small segment along the front of the flooded area, the rest of the oil passing by when the well is drowned. The quantity of oil obtained from a well during the approach of the flood may be larger if it is an old well, because the sand has been more completely drained around the well and oil is being constantly removed, so that the oil tends to move toward this point of low resistance. However, this also creates a tendency for the water to be drawn toward the well, and probably the water reaches and drowns producing wells in advance of the general progress of the flood. In the Coalinga field, California, a tendency has been noted for the approaching water to send out finger-like projections toward the oldest or largest producing wells or where the sand has been most completely drained. Because of this tendency for oil to pass by the wells it is desirable to drill the wells close together and place the wells of each succeeding row in advance of the flood intermediate between the wells in the row ahead to prevent some of the oil from being trapped between wells. This is one of the reasons why wells in advance of the flood are drilled close together in the Bradford field.

FLOODING IN THE APPALACHIAN FIELDS.

A detailed description of the Bradford field and the results obtained by flooding in that field are given in pages 108 to 117, it being considered that Bradford presents the most favorable conditions for flooding and the best experience in conducting a flood. A few instances of flooding in other fields where the yield has been affected are briefly described in the following:

The most notable of the floods which occurred in the early fields was at Pithole, Pa., and has been described by Carll.[a] The flood was caused by lack of effective ways of excluding water and through lack of knowledge of the effects of large quantities of water entering the oil-bearing formations. The flood advanced rapidly and irregularly, and within a period of a few years almost the whole field was drowned out. Some of the wells in the path of the water showed remarkable increases in yield before being drowned, but attempts by operators to foretell or to control the movements of the water were usually unsuccessful. Carll mentions the discovery, after the central part of the field had been flooded out, of several isolated pools of oil trapped on the outskirts.

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[a] Carll, J. F., The geology of the oil regions of Warren, Venango, Clarion, and Butler Counties: Second Geol. Survey of Pennsylvania, vol. 3, 1880, pp. 268-269.

Carll also describes several other isolated pools of trapped oil in the Oil Creek field, Pa. Floods in other Appalachian fields have usually resulted similarly in uncertain movement of the water, temporary benefits, and trapping of oil. Most often flooding has not paid, though occasionally a few properties have been considerably benefited, and it may have been the cause of some unusual yields.

FLOODING AT OIL SPRINGS, CANADA.

Huntley[a] gives the following description of a flood taking place in the Oil Springs pool, in Lambton County, Ontario:

> The entering water may shift the whole body of oil from its original position, the extent of such shifting depending on the dip and shape of the pool and its underground structure. The Oil Springs pool in Lambton County, Ontario, is an example. When the pool was first developed it produced from a shallow "pay," an open vesicular stratum in the Corniferous limestone. The wells were all dug and were cased with Scotch casing of large diameter. At the time of the Fenian raid the field was temporarily abandoned. When operations were later resumed it was found that the lower part of the casing in a great number of the wells had been corroded away, the wells had caved, and great quantities of fresh water from swamps on the surface had flooded the oil-bearing formation. Deeper drilling developed the present "pay" stratum at a lower depth, and the old wells were abandoned, as they could not, of course, be plugged.
>
> In recent years wells drilled through this shallow stratum showed that the water had decreased, and one well struck oil. Other wells were drilled and an attempt was again made to pump off the water.
>
> These operations developed the fact that after the spring rains or any large freshet quantities of fresh water seeping into this porous formation caused the water level to advance up the sides of the anticline upon which the pool is situated, carrying before it a considerable body of oil. By pumping certain wells located at strategic points in progressive rotation, as the water and oil advanced or receded, considerable oil was recovered.
>
> It was noticed that more oil was recovered upon the recession of the water than upon its advance. As the water advanced, a part of the oil was probably caught and retained in the porous irregularities on the roof of the stratum. As the water receded these were again taken up by the main body of oil, increasing its quantity. This supposition is supported by the fact that a few wells would continue to produce a little oil with the water after the surrounding wells had all been flooded by the advancing water. This theory is illustrated in figure 30; 1 and 2 represent wells through which flooding takes place, whereas

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[a] Huntley, L. G., Possible causes of the decline of oil wells and methods of prolonging yield: Tech. Paper 51, Bureau of Mines, 1913, p. 19.

A, A′, B, and C represent wells pumped successively for oil as the water changes the relative position of the oil body.

One well is reported to have yielded 1,300 barrels of oil in three days before failing. As these shallow wells must be worked at great speed to effect a maximum recovery before being again flooded, pumps of large diameter and quick stroke are used.

The reader should note that one advance or recession of the flood removed only a part of the recoverable oil, yet ordinarily the operator must be content with what is obtained during a single passage of the water through the oil sand.

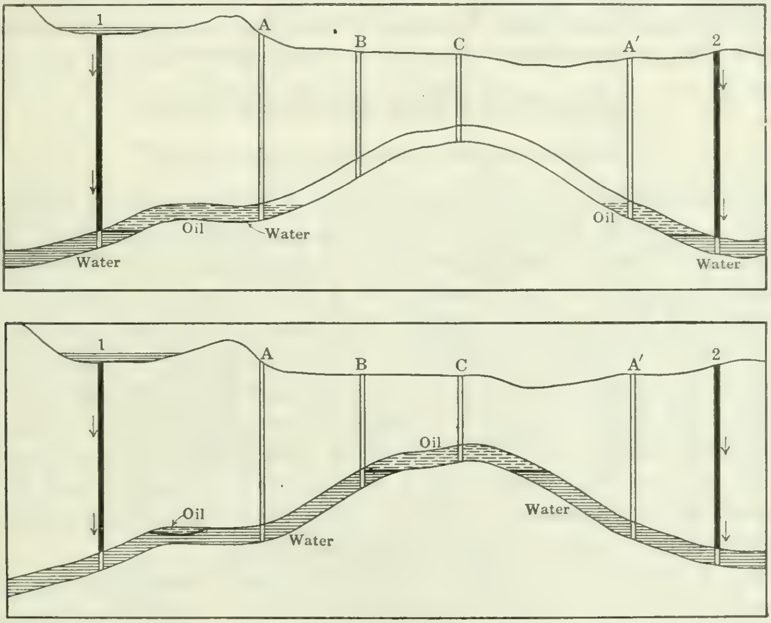

FIGURE 30.—Effects of flood water and arrangement of wells drilled to utilize flood-water pressure.

FLOODING IN THE KERN RIVER FIELD, CALIFORNIA.

The Kern River field in California provides another instance of the effect of flooding where the natural conditions differ considerably from those of the other fields described. Wells in this field are 600 to 1,200 feet deep, the oil is very heavy and viscous and comes from a zone of unconsolidated sands several hundred feet thick, made up of sand lenses interbedded with layers of clay irregular in thickness and extent. Large quantities of water entered the oil sands, some of it coming from strata above and some from strata underlying the oil sands. So much water accumulated in parts of the field that many wells were abandoned and it became necessary to employ special means to rid the field of water in order to continue production. Air lifts were installed by which large quantities of water could be brought to the surface, and by pumping certain wells, called key wells, the water level was lowered in the adjacent parts of the field. The invasion of the water into the sand and its later removal had noteworthy effects upon the productiveness of some parts of the field. Near the center of invaded areas where the wells were most affected by water the productions were considerably decreased, whereas the productions of wells farther away were appreciably benefited. After the air lifts had lowered the water level, those wells which had been benefited decreased in production, and in one part of the field, when the use of air lifts was discontinued for a period and the water reaccumulated, production increased once more in the outlying wells.

FLOODING IN THE BRADFORD FIELD.

HISTORY AND DESCRIPTION OF THE FIELD.

The Bradford field is situated in the northern part of Pennsylvania, a part of it extending over the line into the State of New York. It is one of the largest fields ever developed in the United States, both in area and production. Development started in 1869 and to date (1915) about 230,000,000 barrels of oil, nearly one-third of the total combined productions of Pennsylvania and New York, have been produced from about 85,000 acres, with an average yield of about 2,700 barrels per acre. The wells completed early in the life of the field came in with flows ranging up to several hundred barrels daily, but now the initial yields of new wells average about three barrels daily, whereas the yields of older wells not affected by flooding are only one-tenth to one-half barrel daily.

The Bradford sand is the third in the local series, the first and second sands being practically nonproductive. Ashburner[a] says—

> The Bradford oil sand is the most important economic stratum in the northern tier of counties. It consists of gray and white sand of about the same coarseness as the ordinary beach sand of the Jersey coast; compact, yet loosely cemented. The average thickness of the sand is about 45 feet, and from top to bottom the sandy strata change but little in their general character. It is only when specimens from successive layers are placed side by side and closely examined that any difference in structure can be noticed. The grains of sand are angular, vary but slightly in size, color, and quantity of cementing material, which holds them together in their rock bed.
>
> The same homogeneousness which characterizes the vertical section is found to exist over a considerable horizontal area. In fact, but little change is found to exist in the sand obtained from wells 15 miles apart, or in the sand from intermediate wells.

Operators in the field report that the sand near the top is apt to be hard and practically nonproductive. Most of the sand shows oil, but the large productions obtained during the early lives of the wells came mostly from "pay streaks," which were strata in the oil sand that were no coarser but were less consolidated than the rest of the sand. These "pays" are usually 5 to 10 feet thick and may be in any part of the oil sand, but are usually in the middle part, and there may be two or three "pays" in the same well separated by tighter parts of the sand or by shale breaks. Frequently, in shooting the old wells, the former "pays" do not respond as well as the tighter parts of the sand. Other writers besides Ashburner state that conditions are remarkably uniform throughout the field and that within the productive area not 3 per cent of dry holes have been drilled, for although the individual "pays" may not extend over the whole field, there is usually some pay sand in every well. The strata lie almost horizontal, the average dips being 10 feet per mile, according to Ashburner. On only one flank is the field outlain by salt water, the sand being either barren or containing only gas on the other edges of the field.

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[a] Ashburner, C. A., Report R: 2d Geological Survey of Pennsylvania on McKean Co., 1880, p. 75.

In depth the wells range from 1,200 to more than 2,000 feet, depending largely on the topography. Usually the only casing used is to exclude fresh water, which is found within 300 to 400 feet of the surface in the valleys, and, as drilling conditions are very satisfactory, the wells are, relative to their depth, inexpensive even for the Appalachian field. Pumping costs are low because it is seldom necessary to pull the casing, pumping trouble being infrequent, but on account of the small productions the margins of profit do not permit the producer to make extensive repairs and replacements except during periods of high prices, and usually a well is abandoned if anything goes wrong. Attempts to increase production by gas or vacuum pumping at low pressures as in other fields have been generally unsuccessful and gas pumping is employed only to relieve the wells of back pressure in order to increase the gas supply for fuel and for making gasoline by compression. The wells are not usually pumped by "powers and jacks," but most frequently are pumped "on the beam" (see Pl. IV, *A*) or by air or steam heads (see Pl. III, *B*). Air compressed in compressors driven by gas engines is the most common source of pumping power.

OPINIONS OF THE PRODUCERS ON FLOODING.

Practically the only place where flooding has been even comparatively successful is in the Bradford field, where conditions are exceptionally favorable. Flooding has been going on in this field for over 20 years, although it is only within recent years that it has received favor and attention. The flooding started accidentally from old abandoned wells which had been improperly plugged or not plugged at all. Through these old wells fresh water from sands near the surface entered the oil sand and drove the oil to the pumping wells near-by. At first the flooding was looked upon as an unmixed evil, but when it was found that yields of oil wells were greatly increased and were maintained for periods of several years, and more profits were being derived than otherwise could have been obtained through an indefinite term of years by ordinary pumping, some of the operators concluded that flooding was beneficial and endeavored to make use of the principle to increase the production of their properties.

Though opinion among the operators in this field is by no means unanimous, the majority of the men working in the field appear to favor flooding openly, although most of the larger producing companies are opposed to it.

SOURCE OF THE WATER USED.

As stated previously, mostly fresh water derived from shallow sands is being used for flooding in the Bradford field, and, except for the salt water on one edge of the field, is the only supply in sufficient quantities and under sufficient pressures that is available. The downward migration of this fresh water has seriously affected the supply for domestic use in some parts of the field, and it is reported that springs and wells have gone dry in the vicinity of some properties where flooding is going on. Flooding on an extensive scale in this field as in others is largely dependent upon the available water supply. Doubtless in some fields and in some localities flooding, except on a relatively small scale, would be impracticable from lack of an adequate water supply under sufficient pressure, whereas in other fields or properties a depletion of the fresh-water supply would be seriously objectionable.

The flooding first originated in old abandoned wells as stated, but it has been claimed that some operators have allowed the water to enter wells by raising or splitting the casing or have conducted the water to the oil sand through pipe. Where no provision has been made to prevent the water standing against the walls of the hole, they cave and fill the hole, or mud is carried into the sand and clogs it. Also the water is likely to enter some of the sands above the Bradford sand and be wasted or pass through and drown out other wells in advance of the flood. A number of instances were reported by operators where wells were believed to be drowned out prematurely from this cause.

MOVEMENTS OF THE WATER.

As stated previously, the water moves more slowly every year that a flood continues. At Bradford the water may travel 200 or 300 feet the first year, but in succeeding years the rate will be much less, and when the flood has reached a distance of 500 or 600 feet from the well in which it started, movement will practically cease, unless water is introduced through other wells nearer the front of the flood. Usually it is reported that the rate of progress is about 50 feet yearly. In what was probably the first flood in this field, started about 25 years ago, the water is reported not to have traveled more than 1,000 feet in any direction from the well from which the flood is supposed to have started, and within this area of about 70 acres 14 wells have been abandoned and 10 are still producing. Generally it requires several years, after flooding has started from a well in this field, before any of the surrounding wells are affected, and after the flood has passed the next well the rate of travel is likely to be 35 feet or less each year, so that it would take 10 or 20 years for the water to pass from one well to the next, as usually spaced. Because of this extremely slow movement of the water, it has been the practice to drill new wells close in advance of the flood rather than wait years for the next old well to be affected.

Because of the restricted area which one well will flood and the very slow movement of the water through the oil sand, it would be impracticable to flood the whole of the Bradford field except from many centers. Theoretically, it would be desirable to start at the edges, especially from the lowest levels, and to let the water advance up the dips, driving the oil ahead of it, toward the highest level, but in a large field like the Bradford where the advance is so slow, the properties in the interior of the field would be affected only after an impractical length of time, for at the average rates it would take the water 50 to 100 years to travel 1 mile, whereas the field is about 18 miles long by 12 miles wide. Consequently, if it were desired to flood the whole field, it would be necessary to let the water into the sand at many points. The starting of the many flood centers, even with carefully prearranged plans, would undoubtedly accentuate the losses from trapped oil and would lead to inequitable distribution of benefits.

The movements of the water in the oil sand at Bradford are not as irregular as in most fields where flooding has taken place, yet the water does not spread symmetrically from the center of a flood and its movements can not be predicted. No attempt was made by the writer to determine the effect of the dip of the oil sand in detail upon the movement of the water, but evidently this factor is not as important as other factors, such as the texture of the sand. As has been shown in figure 28, the water does not seek a level and stratify with the oil through the whole thickness of the sand, but advances most rapidly through a comparatively thin part of the sand which offers the least resistance.

PREPARING WELLS FOR "FLOOD OIL."

When an operator becomes aware of an approaching flood he puts the wells that he expects will be affected first into good condition for producing the larger quantities of fluid which must be handled. Usually the wells are shot and thoroughly cleaned out, and the pumping equipment is put into good order. It is becoming the practice to drill pockets 100 to 150 feet below the oil sand, so that when the production increases it will not be necessary to pump the well or pull the casing more frequently than before. If the existing wells are not situated to take the best advantage of the flood, new wells are drilled. As a usual thing, as soon as one well begins to show water and indications that it may be soon drowned a new well is drilled a short distance ahead, sometimes within 100 feet. This close spacing of the wells is made because of the very slow movement of the water and because of the tendency of the oil to pass between the wells if far apart. Where the flood is moving toward a neighboring property, wells may be drilled along the line to prevent oil from being driven across.

EFFECTS OF FLOODING ON ADJACENT PROPERTIES.

One of the chief objections to flooding has been the injury to other properties near by, but advocates of flooding at Bradford maintain that such is not the case there, and that the neighboring properties are more benefited than harmed. They point to the fact that a flood starting on their own property drives the oil toward the neighboring property, which is bound to get some of the oil. In recognition of this tendency for the oil to be driven across the property line and to be lost to the owner of the flooded property, the operators at Bradford drill wells on the property line, it being maintained that practically all the oil from such a well is driven into it by the flood, and that the drain on the neighboring property is not appreciable.

On the other hand, the adjacent producers, although they may receive some oil in this way, are subjected to a flood over which they have no control, and which they are compelled to accept no matter what their beliefs or the local conditions on their own property, nor can they be assured that they will get profits as great as might be obtained by some other method, such as the Smith-Dunn process, the use of which will be made impossible by flooding.

INCREASE OF PRODUCTION BY FLOODING AT BRADFORD.

The effect on a producing well depends largely on its distance from the flood center, and it is commonly reported in the Bradford field that yields of the first wells affected are not increased so much nor does the increase last so long as in the next wells. The first wells affected have sometimes been drowned within a few weeks or months, with little or no increase of production, whereas wells located farther away have produced "flood oil" for several years. It is commonly stated by both advocates and opponents of flooding that the average well has been increased from its former production of one-tenth to one-half barrel daily to one between two and five barrels, which ordinarily is maintained two or three years. Occasionally the yield per well is increased to 10 or 15 barrels daily. One well reported to have been producing only one-third of a barrel daily in 1898, just before being affected by flooding, was reported to be producing two barrels daily in 1916, after being affected 18 years. Some wells abandoned many years ago have been cleaned out and made productive, and it is claimed that in a part of the field formerly always too lean to be profitable, the oil had been concentrated by a flood and production made profitable.

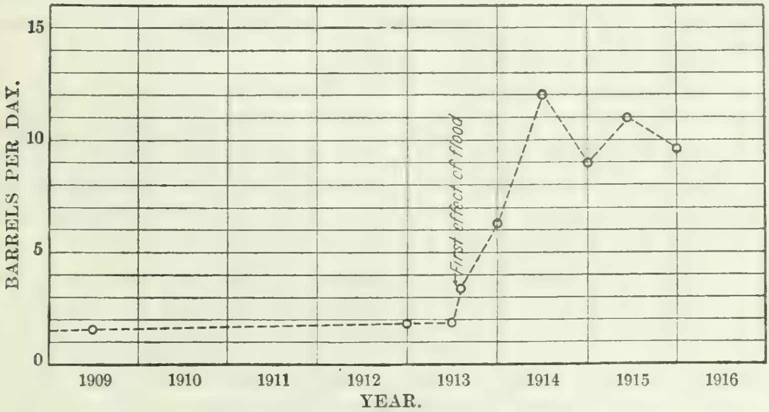

FIGURE 31.—Production curve of a property affected by flooding in the Bradford field. Previous to August, 1913, there were ten wells, later two new wells were drilled and an old well abandoned. Most of the oil comes from two wells, one 263 feet from the flood well. The property was first drilled in 1879 and is in the center of the field. An adjoining tract was too poor to produce, and recently three wells drilled were unprofitable. It has not been affected by the flood.

How the flood affected one property situated in the center of the field is shown in figure 31, the daily yields at intervals during the last 7 years being taken from the company records. Although only a small proportion of the wells were affected by flooding, the yield of the whole property has been increased by five or six times. Records of the same company showed that the average daily yield on nine scattered properties in the field was one-eighth barrel per well for 388 wells, whereas on four other scattered properties on which 18 wells out of 128 were producing "flood oil" the daily production averaged one-half barrel per well. Records of other companies showed increases for individual wells from the usual production of less than one-half barrel to as much as 12 barrels daily. One of the most convincing facts showing the local opinion on flooding is that wells in line with floods sell at prices considerably above the average.

It is claimed by the advocates of flooding at Bradford that to date no property has been entirely flooded, and that not more than 2 or 3 per cent of the wells in the field have been drowned. Reports on wells drilled into a flooded area are conflicting. Some operators report the oil sand to be completely water-logged, whereas others report water only in part of the sand and state that sometimes the well can be pumped, but more frequently there is too much water to do so. An example of a well section through a partly water-logged part of the sand is 26 feet of hard sand showing oil, 10 feet of light brown sand showing much water, and 18 feet of hard sand showing oil. This corresponds to the condition shown between wells B and C in figure 28.

It is evident, from the facts cited, that flooding has greatly increased recovery, for at the low yields reached by the Bradford wells, and the natural decline of 5 to 10 per cent yearly, a well would have to be operated in the ordinary way for an almost indefinite period regardless of profits to obtain the yield obtained from the average well affected by flooding. Moreover, more wells are drilled to the same acreage than formerly. But compared with the capacity of the Bradford sand, the recovery is still low for, as shown previously, the capacity is at least ten times greater than the average recovery in the field to date, which has been about 2,700 barrels per acre. Present information does not permit a positive statement that the sand ever contained this much oil, but there are strong reasons for believing such was the fact, and that the total recovery even by flooding has been and will be only a part of the content of oil.

INCREASES OF PRODUCTION BY MARIETTA PROCESS AT BRADFORD.

Compressed air has been used, so far as known to the writer, on only two properties in the Bradford field to increase production and not extensively in either case. Good increases were obtained, and, considering the circumstances under which the process was used, the results are very encouraging for the use of compressed air or gas. In one instance gas under natural pressure was turned into the sand, but both the volume and the pressure were not sufficient to benefit production. It has been reported that on some properties gas from which the gasoline has been extracted by compressor plants has been returned to the oil sand, and that the dry gas was enriched again after passing through the sand, but it was not stated whether production was appreciably increased. In order to compare the effects of the Smith-Dunn process with flooding, the results on two properties are cited herewith:

Results of using compressed air on two properties in the Bradford field.

FIRST PROPERTY.

Well No.	Former daily yield per well, barrels.	Daily yield per well after applying compressed air, barrels.
1	1	4
2	1	5
3	½ to ¾	4½
4	1½	9
5	1½	5½
Total	5½ to 5¾	28

Production was increased 5 times.

SECOND PROPERTY.

Well No.	Former daily yield per well, barrels.	Daily yield per well after applying compressed air, barrels.
1	½	4½
2	1¼	10
3	½	7½
4	¾	5½
5	½	4
Total	3½	31½

Production was increased 9 times.

On the latter property air was forced into only one well, but benefited six producing wells near by. (See fig. 32.) From experience with the process in other fields it is known that when air is forced into the sand from a number of wells over a large area the production is much benefited. Originally a pressure of 60 pounds was used, which was raised to 80 pounds, with a marked increase in yield of oil; then to 125 pounds, also with a marked increase in yields, but at this pressure the gas from wells near by, which was being supplied to a small town for domestic consumption, began to show more air than was thought desirable, and the use of air was discontinued and natural gas under natural pressure was used, but proved to be insufficient in quantity. Within three months the wells returned to their normal yields.

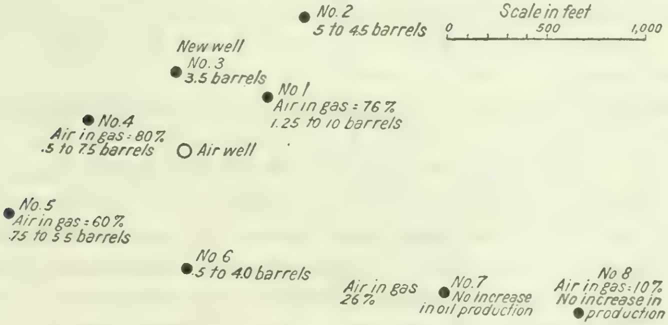

FIGURE 32.—Group of wells in the Bradford field, Pennsylvania, showing the effects of compressed air from one air well on oil and gas of surrounding wells.

These figures indicate that probably yields may be increased in the Bradford field as much by compressed air as by flooding. From the records of properties in other fields there is reason to believe that the increased yields would last at least as long, and probably longer, than with water flooding.

BENEFITS FROM FLOODING AND FROM THE SMITH-DUNN PROCESS.

As the Smith-Dunn process is at the present time the only method yielding results that rival those of flooding at Bradford, comparisons are made between these two methods. Consideration must be given not only to the relative total recovery from flooding and other processes, but to the relative profits derived. One method might result in the recovery of a greater quantity of oil and yet the expense be so large that profits would be much less than for processes where the recovery was not so complete, and it would not be fair to the producer to expect him to employ a process where the recovery was larger but the profits disproportionately small.

Putting the water into the sand costs little or nothing, the only special equipment necessary, if any, being a casing or tubing between the water sand and the oil sand. It is the practice, when a flood is expected, to put old producing wells into thorough condition, which entails some additional expense, but it has been found necessary to drill at considerable expense many new wells spaced much closer than previously in order to protect the property lines or to prevent the passage of "flood oil" between the wells and to get the benefits within reasonable time. While the well is producing nothing but "flood oil" the current pumping costs are increased, but not the relative cost per barrel until the well begins to produce water, whereupon the cost rapidly increases until it becomes unprofitable to pump the well longer. For these reasons the actual expense of flooding may be considerably increased, though in the Bradford field this has been more than compensated by the increased yield. For example, a property with 16 wells affected by flooding showed in one month early in 1916 gross receipts for oil of $1,951, with expenses of $312.08, whereas another property with 14 wells and about the same acreage, a quarter of a mile distant, showed gross receipts of $156.77 and expenses of $83.45, this, however, being only the operating costs and not considering the cost of new wells, etc.

There are no data on which to make a close comparison of the actual cost of the use of compressed air, as compared with flooding, in the Bradford field, but from the data given on the use of the compressed air in other Appalachian fields it may be expected that the costs would not be much larger (exclusive of such royalties as may be paid for patent rights), and probably would be less than for flooding, considering that flooding requires drilling many new wells costing $2,000 to $3,000 or more apiece. Another factor is that the use of compressed air benefits in a short time, usually within a few weeks, every well on a property, whereas flooding takes years for the water to spread from one well to the next, and only a few wells on a property are affected at one time. The quick benefits by air is an especially desirable feature in order to take advantage of a period of high prices. To apply water so as to affect all parts of the property, as compressed air is applied in the Smith-Dunn process, would lead to the trapping of large quantities of oil by the many convergent floods. Another considerable factor is that the flooded property is rendered practically valueless except for the equipment that may be recovered, and probably it will prevent the employing of any other process which might further increase the recovery of oil should they be discovered. On the other hand, the use of compressed air or gas leaves the property in such condition that flooding or any other process might be employed if it should be proved that they were more profitable. At this time, when it is by no means certain that recovery by flooding even under the comparatively favorable conditions at Bradford will be as effective and profitable as the use of air or natural gas, it would seem to be a short-sighted policy to use any process which would permanently damage the property until it has been demonstrated whether or not the use of compressed air or gas would be more beneficial.

MORE EFFECTIVE UTILIZATION OF NATURAL PRESSURES.

The recovery of oil may be divided into two stages: (1) The expulsion of the oil by the natural forces, and (2) the use of external forces after the natural forces have been virtually exhausted. So far only the second phase has been considered, but it is possible to increase recovery by more effective utilization of the natural gas found associated with the oil underground. Some information has been given on this subject by Huntley[a] in Technical Paper 51, by Arnold and Garfias[b] in Technical Paper 70, and by McMurray and the present author[c] in Technical Paper 130. Discussion is limited here to increasing the so-called efficiency of expulsion, and the various mechanical devices for raising oil to the surface are not considered.

There is a definite and limited amount of natural energy associated with the oil in each field, and largely upon how effectively that energy is utilized to expel the oil from the sand will depend what proportion of the oil in the sand may be recovered, for evidently the exhaustion of a well is caused more by the exhaustion of the natural expulsive forces than by the depletion of the supply of oil. If the natural gas associated with the oil is permitted to escape unrestricted and without performing the greatest amount of work possible, the producer is lessening the quantity of oil that may be obtained by natural means. Every foot of gas produced wastefully may be considered to represent a quantity of oil that should have been brought to the surface by using the gas effectively. It appears logical to gage the efficiency of production methods by the relative volumes of gas produced with the oil at the same well. If, for example, a change in method reduced the volume of gas produced with each barrel of oil from 2,000 to 1,000 cubic feet, much more oil could be recovered eventually, even though the actual daily production of oil were reduced a little temporarily.

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[a] Huntley, L. G., Possible causes of the decline of oil wells and suggested methods of prolonging yield: Tech. Paper 51, Bureau of Mines, 1913, 32 pp.

[b] Arnold, Ralph, and Garfias, V. R., Methods of oil recovery in California: Tech. Paper 70, Bureau of Mines, 1914, 57 pp.

[c] McMurray, W. F., and Lewis, J. O., Underground waste of oil and gas, and methods of prolonging yield: Tech. Paper 130, Bureau of Mines, 1916, 28 pp.

Few have realized to what a degree recovery is dependent upon the efficiency in utilizing the natural gas found associated with the oil, nor that it is possible to regulate, at least partly, the conditions of expulsion. Little effort has even been made to follow out the principles of utilizing gas pressures in practice, and on account of conflicting interests along property lines and other difficulties it may often be impossible to follow out these principles to their full logical conclusion, but even with such limitations the conservation of the natural energy offers considerable promise for increasing production. Because so little has been done to develop this phase of recovery, all that can be done in this publication is to review the principles and to suggest a few lines for experimentation in the field.

From the use of compressed air for increasing production, much valuable information may be derived that is applicable to the oil fields before the exhaustion of the gas. Heretofore it has been difficult to trace the underground movements of the oil and the gas and to connect cause with result, but in the Smith-Dunn process this can be done more readily and the effects of the passage of various volumes of a gas under different pressures can be noted for the different conditions found in the oil sands. Many of the principles disclosed by the practical operations of this process also apply to production by natural means, such as "by-passing," "blowing through," and other factors that cause inefficiency of expulsion. Though the operator will not have control over the source of energy as in the Smith-Dunn process, nor over the natural underground conditions, he will have some control over the efficiency of expulsion by regulating conditions at the producing well, and a study of how this is done in the use of compressed air will be of greatest aid.

Maintaining back pressures on wasteful wells has been found to be the most effective way of overcoming the waste of air from by-passing in using the Smith-Dunn process. By this means air that otherwise would pass through the sand without doing much work is forced to take channels where it will move oil. Usually the daily yield of such wells is reduced, but sometimes it is found that the production of oil is actually increased. It is suggested that the principles embodied in the method of maintaining back pressures on the oil sand by a liquid seal, as shown in figure 4 (p. 45), could also be used advantageously on wells before the supply of natural gas has been exhausted, in order to prevent the wasteful escape of gas beyond the amounts that would expel the oil most efficiently. The benefits may be considered to extend beyond the well itself, for one well may waste much gas that otherwise would contribute to the production of other wells on the property.

Quick[a] has made some interesting observations on the effects of letting water stand in the hole while the wells were being drilled through the oil sands and during the periods of flush production. Because of the lack of effective ways of excluding water, most of the wells in the early fields in Pennsylvania had water standing in the hole when drilled and Quick observes that such wells produced more oil than has been the case since the practice has been to drill the wells in dry. The column of water in the hole provided a liquid seal that prevented the excessive escape of gas and consequently more of the energy was used in expelling oil from the pores in the sands. Moreover, the water prevented to a large extent the lowering of temperatures from the expanding gas and the vaporization of the gasoline in the oil which would have caused the deposition of paraffin and waxy sediment in the pores of the sand.

The following method, described in Technical Paper 130,[b] was first applied to gusher wells in California that, if allowed to flow unrestricted, would " sand up " or be likely to get beyond control:

> In some of the California fields wells capable of producing as much as 10,000 to 15,000 barrels of oil a day, and making in addition several million feet of gas, are restricted to a flow of 1,000 barrels a day or less, with a comparatively small flow of gas, by closing the well to a five-eighths-inch or one-inch opening. It has been found that the ultimate flush production from such restricted wells has almost invariably been more than the unrestricted flow from neighboring wells.

It is necessary to experiment on each well to find the size of opening for best results and from time to time this must be changed as conditions change at the well. If the opening is too small only gas may be let through. The method is applicable only to some flowing wells, and about the same results have been obtained by maintaining back pressures through gas-separating traps. The effect on the rate of production is variable; in some cases considerable back pressure may be held on the well without materially diminishing production. The saving of vapors in the gas traps has in a number of instances increased the yield of oil.

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[a] Quick, M. W., Has Pennsylvania 370 years of oil left?: Nat. Petroleum News, vol. 5, October, 1913, pp. 1–3, and following issues.

[b] McMurray, W. F., and Lewis, J. O., Underground wastes in oil and gas fields, and methods of prevention: Tech. Paper 130, Bureau of Mines, 1916, p. 17.

Though it has not been established definitely, there is reason to believe, from experiments and from experience with the Smith-Dunn process, that there are pressures of maximum efficiency above which energy will be wasted in expelling the oil by gas or air. The natural pressures found in an oil well may be above this most efficient pressure, and in such a case it seems possible that efficiency may be increased by maintaining back pressure on the well. The maximum pressure will vary from well to well and during the life of each well, and what back pressure to hold can be found only by trial and by gaging the relative volumes of gas to oil. In a flowing well in California it was found that a certain back pressure not only decreased the relative volume of gas to oil, but actually increased the yield of oil.

One of the most obvious wastes of energy is in wells where the top of the productive sand carries gas only. If the gas in this part of the formation is not restrained, it will escape rapidly and diminish the pressure quicker than in the oil-bearing part of the sand, and is likely to become a by-pass channel into which gas given up from the oil sand will be fed and its energy wasted without doing its quota of work. Furthermore, the flow of gas into this part of the sand is likely to carry oil with it, much of which will be retained in the pores and can not be recovered. A noteworthy instance is reported from the Cushing field, Oklahoma.[a] It has often been the practice not to separate the gas-bearing from the oil-bearing parts of the formation in order to aid the flow of oil, but the benefits, if any, are temporary and in the long run it would pay to separate the gas from the oil by casing or packers, that the gas may find exit only through the oil-bearing part of the sand and aid in expelling the oil rather than to become a means of wasting gas and decreasing recovery.

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[a] McMurray, W. F., and Lewis, J. O., Underground wastes in oil and gas fields, and methods of prevention: Tech. Paper 130, Bureau of Mines, 1916, p. 18.

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